**AN ENHANCED FUSELAGE ULTRASOUND INSPECTION APPROACH FOR ISHM PURPOSES**

THESIS

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AFIT/GSE/ENV/12-M12

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THESIS

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## Abstract

This effort constitutes a systems engineering approach in which the materials science, ultrasound structural health monitoring, flight and maintenance operations, and relevant aeronautical policies and programs are involved to explore the evolution and characterization of structural cracks in aircraft fuselage structures in which the loads are varying. During flight, an aircraft fuselage skin and structure are subjected to varied cyclic loads, which can cause embedded cracks and other damage features to change their characteristics due to loading effects. The current research is based in the application of finite element modeling techniques using COMSOL and PZFLEX software to characterize the behavior of a crack under static loads as well as experimental techniques to observe the behavior of cracks under different static loads, with the goal of understanding the interaction of ultrasonic energy with opening-closing crack features. Specimen testing under tensile loads were considered, where crack detection and crack characterization were studied for bonded piezoelectric sensing and guided ultrasonic waves useful in structural health monitoring applications. The results suggest that crack detection and crack sizing accuracy can be impacted by load-induced, crack opening-closure effects, where linear elastic loading of the structure resulted in linear changes in the ultrasonic signal response.

*I dedicate these pages to my lovely mother; a woman who spent her life doing the things she had to do so her sons could grow up and do the things they want to do and my two wonderful brothers. The power of four will be always more than one's. For you that someday will be with me. Praise the Lord, oh my soul, for it is well.*

## Acknowledgements

Too many words to be said in such a small room…

This would not have been possible without the loving support and understanding of Ms Annette Robb, who daily fights not only to get her work done, but to show the friendly, lovely and human face of the US to the International Military Community. Because of her I feel commitment with the USAF goals. I would like to express sincere appreciation to my faculty advisor, Dr. Som Soni for his guidance and steadfast support before and during the course of this thesis effort. I would like express my profound respect to Dr. James Blackshire whose expertise, willingness and passion for teaching and researching greatly strengthened my academic knowledge to complete this work. I would also like to thank my academic advisor, Dr. David Jacques, for his support during master degree coursework I would like to thank Jacob Kimball English, my sponsor, my advisor, my friend, my brother and his beautiful family. I would like to thank Mr. Vic and Marsha Grazier, what a wonderful souls. Thanks to John Machuca and his lovely family, Travis Pond, Michael Molesworth and all my classmates; without their daily reflections, this would not have been possible. Many thanks to the glorious Colombian Air Force *"Asi se va a las Alturas"*

Francisco Ospina

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## List of Abbreviations

| | |
|---|---|
| AC | Advisory Circular |
| AFRL | Air Force Research Labs |
| AFSO21 | Air Force Smart Operations for the 21st Century |
| AFT | Accelerated Fatigue Testing |
| AIRMAN | Aircraft Maintenance Analysis |
| ANOVA | Analysis of Variance |
| ASHMS | Aircraft Structural Health Monitoring System |
| ASIP | Aircraft Structural Integrity Program |
| CB | Computer-Based |
| CBM | Condition Based Maintenance |
| CFR | Code of Federal Regulations |
| COD | Crack Opening Displacement |
| DT | Damage Tolerance |
| DTA | Damage Tolerance Analysis |
| FAA | Federal Aviation Administration |
| FCL | Fatigue Critical Location |
| FEM | Finite Element Modeling |
| FEMA | Finite Element Modeling Analysis |
| FG | Functions Generator |
| FMP | Fatigue Management Program |
| FSK | Frequency Shift Keying |

| | |
|---|---|
| HVM | High Velocity Maintenance |
| ICAO | International Civil Aviation Administration |
| IDT | Interdigital Transducer |
| INCOSE | International Council on Systems Engineering |
| ISHM | Integrated Structural Health Monitoring |
| JAA | Joint Aviation Administration |
| KHz | Kilohertz |
| MTS | Material Test System |
| MCC | Maintenance Control Center |
| MHz | Megahertz |
| MSD | Multiple-Site Fatigue Damage |
| NAARP | National Aging Aircraft Research Program |
| NDE | Nondestructive Evaluation |
| NDI | Nondestructive Inspection |
| OSC | Oscilloscope |
| PC | Personal Computer |
| POD | Probability of Detection |
| PZT | Piezoelectric Transducer |
| RTASHMS | Real Time Aircraft Structural Health Monitoring System |
| SAW | Surface Acoustic Waves |
| SE | Systems Engineering |
| SIP | Supplemental Inspection Programs |
| TOA | Time of Arrival |

| | |
|---|---|
| USAF | United States Air Force |
| WFD | Widespread Fatigue Damage |

AN ENHANCED FUSELAGE ULTRASOUND INSPECTION APPROACH FOR ISHM PURPOSES

# I. Introduction

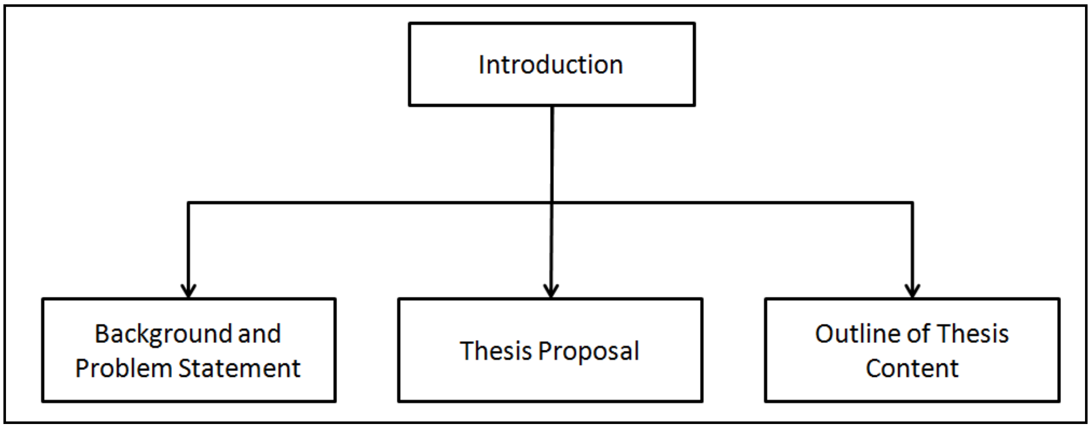



Figure 1: Chapter 1 Decomposition

This chapter (Figure 1) introduces the background that justifies the need for the implementation of an enhanced technique to detect, size and track cracks in aircraft fuselages subjected to cyclic fatigue loads. In addition, it states the reason this problem was selected and the available capabilities to do research and propose a consistent alternative to solve the problem.

## 1.1 Background and Problem Identification

The aviation industry has experienced a remarkable growth since World War II. This growth has been based upon specific military and commercial design requirements for survivability, weapon capabilities, maintainability, comfort, safety, speed and many others factors.  Requirements for improved passenger comfort, for example, led to the implementation of pressurized cabins by Lockheed in 1943, which has since become a standard practice in the industry.

An unintended consequence of this innovation, however, soon became apparent, when in 1954, the British de Havilland Comet, the largest diameter pressurized fuselage aircraft with windows, had three catastrophic airframe failures resulting in the total loss of the aircraft.  All passengers and the entire crew died and the fleet was grounded leading to the end of operation of this short-lived fleet.  More recently, in April 1988, the Aloha Airlines commercial flight 243 suffered an explosive decompression event during flight, where repeated pressurization cycles and material degradation and fatigue were considered to be major causes of the event.  Since then, recurrent incidents involving explosion decompression have threatened the aviation safety.

An important outcome of these unfortunate accidents involved the identification of pressurization-induced  multi-site fatigue damage (MSD) as a critical component of flight safety.  In particular, the detection of small cracks at multiple sites in close proximity to each other was identified as a critical need to ensure safe flight operation. As a result, the use of nondestructive evaluation (NDE) inspections occurring at specific time intervals has helped to detect cracks and other damage features in aerospace structures for many decades.

In this research effort, the role of NDE measurements are studied with respect to crack detection in a structure with varying load.  The connection of this research with pressurization-induced MSD lies in a new area of damage sensing called integrated structural health monitoring (ISHM), where NDE sensors are permanently attached to a structure, providing real-time detection of cracks while an aircraft is flying. The role of crack-closure due to varying load conditions in the structure become important for ISHM, where the sensing methods can be affected by closure of a crack in compression. Finite element analysis (FEA) models and experimental studies are used in the present effort to understand the effect of load on crack sensing for ultrasonic ISHM sensors, where a linear change in ultrasonic signal response was observed for linear variations in tensile loading of a cracked structure.

### *1.2 Thesis Proposal*

AFRL, led by the Nondestructive Evaluation Branch of the Materials & Manufacturing Directorate is interested in developing a framework to quantify the Crack Opening Displacement (COD), the crack opening and closure upon load application, and to develop techniques to predict the crack behavior for detection, sizing, and tracking purposes. Current maintenance operations require more effective approaches to significantly improve the knowledge of the crack behavior by using the available tools and equipment. This research proposes to explore the feasibility of an innovative procedure to estimate the COD and the crack opening and closure behavior as well as how those characteristics can be used to detect, size, and track cracks. This goal is accomplished by reviewing analytical models, performing computer-based simulations and conducting in-situ experiments to lay down the foundation of scientific, systems engineering and operations knowledge for ISHM purposes.

### *1.3 Outline of Thesis Content*

Chapter 2 deals with background consisting of the importance of aircraft pressurization in the problem domain, the aircrafts aging trends and their effect in the growth of fatigue cracks. There are reviewed relevant concepts such as multiple-site fatigue damage, widespread fatigue damage and small fatigue crack. Essential load induced crack opening/closure and ISHM ultrasound sensing concepts are discussed to finally identify the systems engineering elements and the current maintenance requirements and policies. This chapter also addresses additional external research and development required to support the system proposed herein. The information presented here is required for the analysis of the proposed system. In Chapter 3 is presented the experimental setup, modeling and in-situ testing tools and equipment. A detailed description of tools and equipment used is presented since this experimental setup might be used in future replication tasks. Chapter 4 is limited to the results of the experiments involving either the three specimens under testing or the LT-19 specimen. Since the objective of this thesis is to explore the feasibility of the detection system and how it can be integrated into the current maintenance and operations procedures, the specific results for specimens LT-10 and LT-13 are not included. Finally, chapter 5 contains conclusions, reflections and future thesis prospectus based on the research conducted during this study.

## *II. Literature Review*

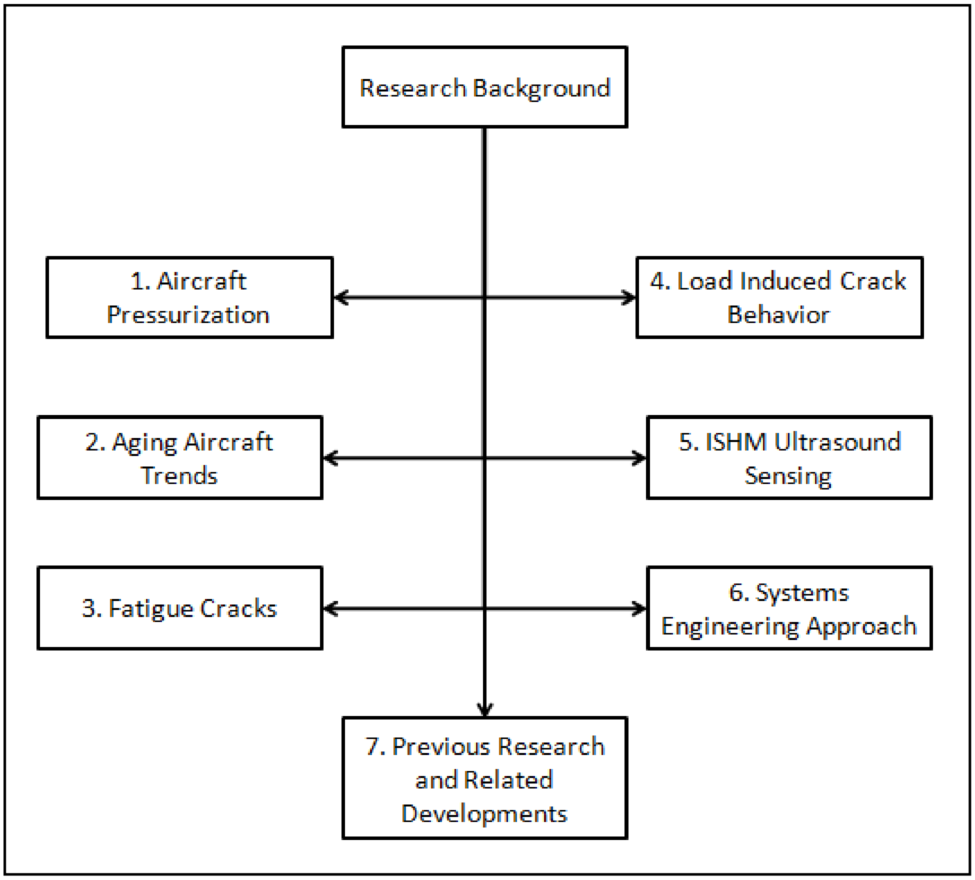



Figure 2: Chapter 2 Decomposition

This chapter provides the background to support the detection system proposed by this research.

### *2.1 Aircraft Pressurization*

Aircraft cabin pressurization, as a concept, has not been an easy task to accomplish. Pre WW-II aircraft did not employ cabin pressurization. Shortly after WW-II, the first commercial jet transport with cabin pressurization was introduced creating additional passenger comfort by flying above the majority of weather disturbances, which have been found mainly to occur in the troposphere (up to 10 Km. of height) and allowing near sea-level air pressure breathing environments.

Unfortunately, the first pressurized jet transports had three mid-air disasters in the early l950's due to explosive cabin depressurization caused by cyclic fatigue from cabin pressurization cycles. The present day science of aircraft fatigue analysis and fracture mechanics was born from these disasters. Recent airline disasters because of cyclic fatigue have focused world attention once again on the safety aspects of pressurized aircraft cabin structures (Craig, 1990).

### *2.1.1 Effect of Aircraft Pressurization in Crack Growth*

Although the absolute pressure involved, around 5-10 psi, may seem benign, the structural deflections or expansion of pressurized fuselage cabins can involve several inches, and with these deflections fatigue cracking usually develops. On the first pressurized transport, these cracks grew from the corners of the square cabin windows. In recent accidents, fatigue cracking has progressed catastrophically from pressure bulkheads, fuselage skin lap joints, rivets and cargo compartment door areas. All of these failures have been attributed to long term fatigue damage caused by cabin pressurizing cycles, possibly assisted by corrosion of the aluminum alloy structures.

The major commercial transport manufacturers did not intend, or design for, their aircraft to be subjected to infinite service life. However, the changing face of the commercial airline industry has resulted in airlines and military forces utilizing aircraft exceeding 50 years in age and nearing 100,000 flight cycles (one cycle is one takeoff and landing event). These two conditions of calendar age plus flight cycles feed upon each other, i.e. calendar age manifests itself as corrosion of the structure which then allows further accelerated progression of fatigue cracking induced by flight cycles (Craig, 1990).

### *2.2 Aging Aircraft Trends*

Structural health concerns are focused on aircraft with increasing age. Civilian and military aircraft inventories have both experienced a gradual and continual increase in the average aircraft age. In the civilian general aviation market, the high cost of new aircraft reduced new aircraft purchases resulting in legacy aircraft usage beyond the original design service life (Figure 3) [2].

Civilian commercial and general aviation aircraft inventories have both increased in average aircraft age. The high cost of new aircraft forced the civilian general aviation market to purchase and maintain legacy aircraft beyond the original design service life.

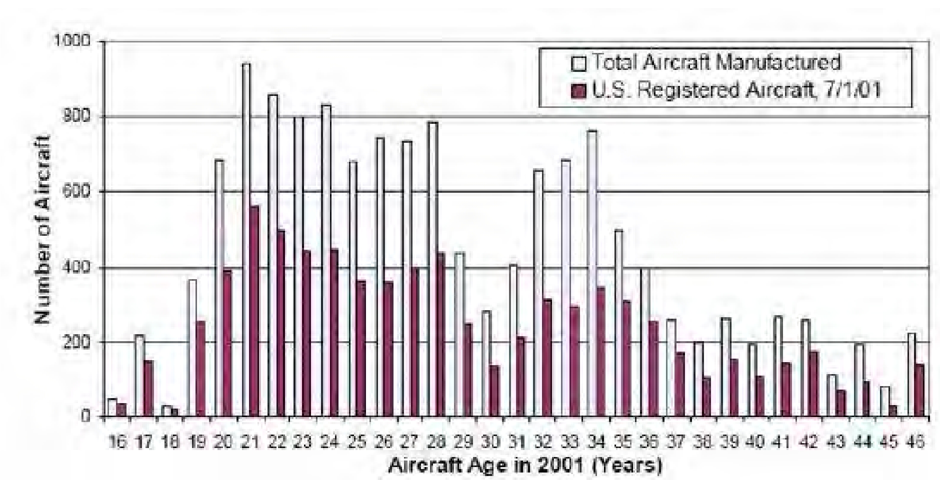



Figure 3: Number of Aircraft and Aircraft Age [2]

From 1971 to 2006 the overall Air Force fleet has declined in number from more than 10,000 aircraft to approximately 7,000, yet the average age of these aircrafts increased to almost 24 years. The current and predicted trend resulted from this analysis are shown in figure 4. (Gen (r) Carlson, 2006).

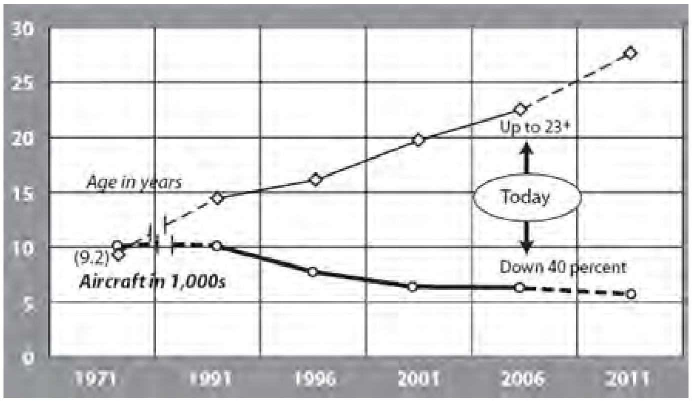



Figure 4: Number and Age of Air Force Aircrafts [15]

The United States Armed Forces are aging with a positive slope tendency. Figure 4 and figure 5 show the same trend in the air force and, additionally, figure 5 compares the Army, the Navy and the Air Force.

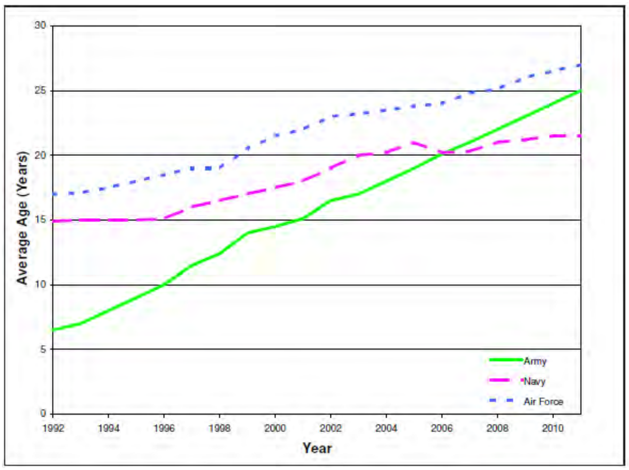



Figure 5: US Armed Forces Average Fleet Age [2]

### *2.3 Fatigue Cracks*

Structural fatigue resulting from repetitive operational use and loading is the primary cause of structural failure. For example, aluminum, the most widely used type of material in aircraft design and the one used in this research, does not have an endurance limit; therefore, it accumulates damage with use. Use generates fatigue, so to avoid fatigue would mean to avoid use. This is not practical, thus fatigue is not preventable. Fatigue must be understood and monitored to mitigate the potential catastrophic effects [2].

Fatigue generally results from two types of loading: low cycle and high cycle. Flight maneuvering and aircraft loading generate low-cycle fatigue. Low-cycle fatigue usually has a higher amplitude and lower frequency than high-cycle fatigue. Vibration from aerodynamic, mechanical, or acoustic sources leads to high-cycle fatigue. The loads generated from flight maneuvering and aircraft loading can be estimated quite well during aircraft design. These estimations remain quite accurate as long as the aircraft operates within the original design parameters for operational use. In contrast, the high-cycle loads can also be estimated during aircraft design, but these loads will most probably change later in the aircraft's life. This phenomenon occurs due to changes in the response of the structure due to wear, repairs, structural cracks or variations in operational use or aircraft configuration [2].

Critical length is defined as the crack length that will cause structural failure of the fatigued element. This assumes a single crack in an element. Widespread fatigue damage (WFD) complicates the problem further. The existence of multiple-site fatigue cracks of sufficient size and density to decrease strength is WFD. The multiple cracks may occur in the same structural element or adjacent structural elements. Whenever and however cracking occurs, the more accurately it can be predicted and the effects on structural strength analyzed; the longer aircraft can be safely flown prior to maintenance action or aircraft retirement. [2]

Fatigue cracks by nature can be extremely small in size, on the order of 1 µm in width, and 1 mm in length, at 100 µ in depth depending on the number of cycles. In comparison, the fuselage surface area in need of inspection for a current narrow body transport is about 550-850 square meters. Wide body transports have fuselage surface areas approaching 1500 square meters. Existing inspection techniques, concepts and philosophies for detecting and sizing very small cracks over very large areas are constantly challenged and are often not sufficient. Lack of knowledge of fatigue damage, unknowns involved with fatigue analysis, unrealistic fatigue testing, and inattention to detail during inspections and simply missed or deferred inspections spell disaster (Craig, 1990).

### *2.3.1 Multiple-Site Fatigue Damage*

MSD is a common phenomenon for aging aircrafts and its main property is the existence of interacting fatigue cracks at different sites of a structural component. Commonly, it occurs along the rows of fastener holes in aircraft wings and fuselage and can cause the unallowable decrease of the residual strength of the structure and as a result the catastrophic failure (Timoshtchenko, 2005). For MSD to occur, it is likely that the same damage processes occur at multiple locations within the same structural element. In the case of the lap joint, similar damage processes occur at multiple rivet locations along the same rivet row. The thorough understanding of MSD is required to develop deterministic methods for predicting and timely detecting the onset and growth of small fatigue cracks in aging airframe structure (Piascik, 1998).

Figure 6: Multiple-Site Fatigue Damage (Murakami)

### *2.3.2 Small Fatigue Crack*

Physically small fatigue cracks with dimensions less than about 2 mm can be classified into three categories: microstructurally small cracks, mechanically small cracks, and large cracks. Microstructurally small cracks with lengths on the order of the grain size show anomalously fast, irregular propagation rates. Because of microstructural inhomogeneities, the crack propagation behavior has statistical characteristics. For mechanically small (microstructurally large) cracks, an appropriate choice of fracture mechanics parameters gives the same propagation law as for large cracks, because the material is now regarded as homogeneous. Large cracks whose length is approximately ten times the grain size are treated by the conventional methodologies of fracture mechanics (Tanaka). Most of fatigue life is spent in crack initiation and small crack growth. The small cracks have been observed to grow faster than long cracks and a significant crack lifetime elapses before a small crack transitions to a long crack (Suresh, 1985).

### *2.3.3 Prevention against Cracks*

Cracking is such a critical and common safety issue that aircraft designers account for its occurrence during design. Typically, aircraft designers account for structural cracks through two design approaches: safe crack growth design and fail-safe design. Safe crack growth is typically used for high-performance combat aircraft where weight is a considerable consideration. Safe crack growth design ensures that the maximum probable undetectable initial manufacturing flaw will not grow to critical size in any critical structure during the operational life of the aircraft. This requires a considerable engineering analysis using crack growth prediction models. Since the prediction models are not precise, a large safety factor is introduced. Additionally, concerns exist for aging aircraft which do not account for all possible Fatigue Critical Locations (FCLs) in the original analysis. Other locations may also become critical in aging aircraft. Fail-safe design relies on multiple, redundant load paths or crack arrest features to mitigate the effects of cracks. This design approach is typically used in larger aircraft. Understanding aircraft structural failures and their causes is a complex problem. While work is still being done, predictive models are not always accurate. Detection of structural damage can be difficult. Overall, structural integrity issues for aging aircraft are particularly difficult because the damage under consideration consists of multiple interacting flaws and the crack sizes are often in a range where the phenomenon is complex and not well behaved [2].

## 2.4 Load Induced Crack Behavior

### 2.4.1 Linear Elastic Crack Opening Behavior

Numerous experimental and theoretical studies give conclusive evidence of the presence of a non-zero crack tip opening displacement as a result of the plastic flow in the material (Parton and Morozov, 1978). The size of the region covered by the plastic flow depends on the material properties and the loading conditions. However, we are trying to prove with this research that it is possible to quantify the crack opening displacement in the same material under a variety of loadings for structural health monitoring purposes. The Orowan-Irwin concept (Parton, 1992) establishes that the plastic zone is small compared with the crack length, but the quasi-brittle region contributes to closing and hiding the crack if using conventional health monitoring detection techniques. This concept enables the assumption of a non-zero value of the displacement at the crack tip and this fact has an appreciable effect only in the vicinity of the crack tip; the size of this vicinity being at the same order of magnitude as the non-zero crack opening displacement. Outside this vicinity, the strain, displacement and stress fields are described by the linear theory of elasticity. Thus, the use of the Orowan-Irwing concept makes it possible to preserve the solution of the elasticity theory and it accepts the possibility to consider that once applied a load, the COD of every pair of points on either side of the crack, will hold a linear tendency.

#### 2.4.1.1 Theoretical Crack Opening and Closure Sizing

Real cracks are often subjected to the action of externally applied or residual compressive stress fields; the spatial distribution and intensity of which may depend considerably on the particular configuration or the history of the cracked material system. Those stresses act like a clamp on crack faces, leading them to contact at the crack tip. Wolf Elber (1968) showed that fatigue cracks in sheets of aluminum alloys close before all tensile load is removed. He attributed these effects to the residual compressive stresses which exist, at unloading, in plastic zones in the wake and the front of the crack. This phenomenon was defined as *the plasticity induced crack closure.* This phenomenon is well explained in a research paper:

> During unloading the upper and lower fatigue crack surfaces must touch while the specimen is still under tension. Crack closure starts at the crack tip which removes the singularity of the stress distribution at the crack tip. During reloading the crack tip will open at a positive stress level, $K_{op}$. Only the stress range with a fully open crack tip, $\Delta K_{eff} = K_{max} - K_{op}$, is assumed to determine the crack length increment, $\Delta a$. The concept of a $\Delta K_{eff}$ is now generally accepted and used in prediction models, but it should be realized that the concept includes the assumption that the fatigue crack extension $\Delta a$ is fully controlled by $\Delta K_{eff}$ (Schijve, 2007).

For a given material and set of test conditions, the crack growth behavior can be described by the relationship between cyclic crack growth rate $\frac{da}{dN}$ and the stress intensity range $\Delta K$. The stress intensity range accounts for both stress level and crack length. Mathematically, the plasticity induced crack closure is defined as follows (equation 2.1):

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^{m} \qquad (2.1)$$

Where C and m are constants for the intermediate region available in materials science literature. The value of m is important and represents the degree of sensitivity of the growth rate to stress. Equation 2.2 accounts for the $\Delta K_{eff}$ relation:

$$\Delta K_{eff} = K_{max} - K_{op} \qquad (2.2)$$

$K_{op}$ corresponds to the fully open crack. To take into account the stress ratio $\boldsymbol{R}$ that affects the crack growth rate, Elber proposed the empirical relation (equation 2.3) for aluminum alloy 2024 – T3:

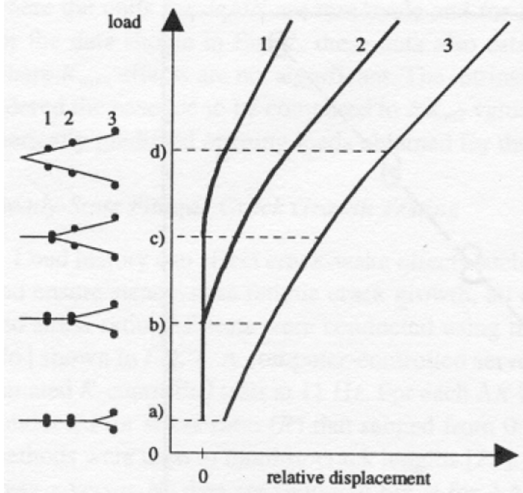
$$\frac{\Delta K_{eff}}{\Delta K} = 0.5 + 0.4R \qquad (2.3)$$

Despite its limitations, the linear model proposed by Elber seems to be of great relevance and accurately defines the crack opening and measurement of corresponding load (Bouami and De Vadder).

### *2.4.2 Near-Crack-Tip Displacement Measurements*

The characterization of near-threshold closure behavior is especially complex. Analytical solutions can be found in (Parton and Morozov, 1978). It is likely that various crack closure mechanisms such as plasticity, roughness, corrosion product and oxide layers are dependent on many variables and combine to alter the crack shape.

Direct and accurate closure measurements are difficult to make, and correct interpretation of these measurements are widely debated, making the quantification of near-threshold effects extremely complex from the mathematical point of view. However, the crack opening behavior has been translated into a schematic idealization (Figure 7) of elastic-plastic load-versus-relative-displacement response. For a particular material, its properties will slightly modify this idealization.




| | LOCATION | | |
|---|---|---|---|
| LOAD | 1 | 2 | 3 |
| d) | f.o. | f.o. | f.o. |
| c) | l.o. | open | open |
| b) | closed | l.o. | open |
| a) | closed | closed | open |

Figure 7: Near-Crack-Tip Configuration and the Corresponding Load-Versus-Relative-Displacement Behavior as the Remote Load is increased. [17]

At minimum load, point (a), much of the crack faces are in contact. However, location 3 is far enough behind the crack-tip so that the faces are open at minimum load, resulting in positive relative displacements at minimum load. As the load increases to point (b), more of the crack faces separate, and the slope of the relative-displacement-versus-load plot measured from location #3 decreases continuously. Finally, loading the crack to point (d) results in a fully opened crack. [17]

### *2.5 ISHM Ultrasound Sensing*

This Non-Destructive Inspection (NDI) technique is based on ultrasonic pulse-waves launched into materials to detect flaws or to characterize materials, where there are several commercial products with specific characteristics and capabilities. This research used Piezoelectric Transducers (PZT) and the Interdigital Transducer (IDT), which will be discussed in the next sections.

### *2.5.1 Effective and Real Crack Ultrasound Detection*

The action of the compressive stress field discussed in section 2.4 can significantly alter the probability of detecting a crack-like defect by means of ultrasonic waves by bringing faces into contact, reducing in this way the material discontinuity to which an ultrasonic wave is sensitive (Pecorari, 200). When the crack is being compressed by its surrounding stress field, the *real crack length* is underestimated by the ultrasound wave. The *effective crack length* that results from this underestimation is less detectable and traceable regardless of the method of detection being performed (Figure 8).

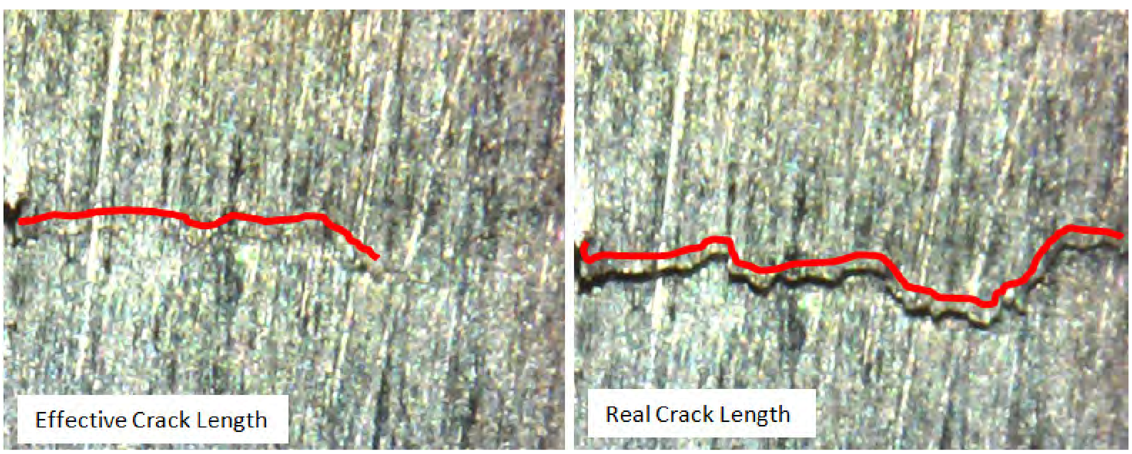



Figure 8: Real (right) and Effective (left) Crack Length

Since the ultrasound wave senses air gaps, when there exists touching points in the crack face, the real length is underestimated. As shown in figure 9, the reflected wave weakens the ultrasound signal and affects the peak-to-peak outcome (the peak-to-peak outcome will be discussed farther in chapter IV) because the receiver sensor is not sensing the same signal strength as the original signal. In figure 9, there is applied a 99.6 lb axial load, so the crack is partially open.

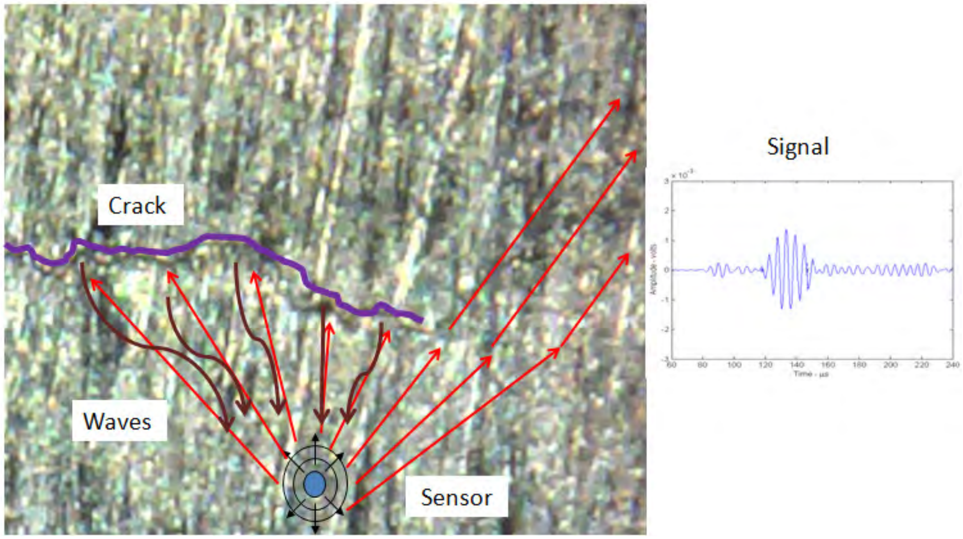



Figure 9: Effective Crack Ultrasound Reflection

In figure 10 a 351.4 lb axial load was applied. The image is intended to depict that the crack is completely open and a full ultrasound signal reflection produces a greater impact in the peak-to-peak differential signal.

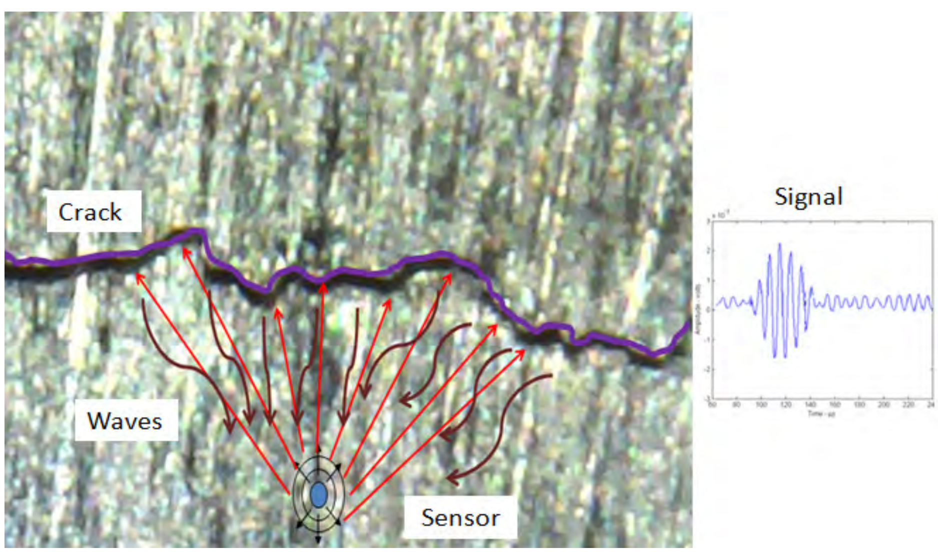



Figure 10: Real Crack Ultrasound Reflection

### *2.5.2 Piezoelectric Transducers PZT and Lamb Waves*

In 1880 Jacques and Pierre Curie discovered the piezoelectric effect. The piezoelectric effect is the phenomenon of mechanical strain applied to a material producing a proportional electrical field.

The introduction of relatively inexpensive PZT disks allows Lamb waves to be excited and detected within a thin plate simply by gluing the transducers directly to the surface and driving the PZT with a known electric voltage waveform. Lamb waves traveling through a material, such as aluminum, have wave speeds that are dependent upon their frequency. The initial Symmetric and Antisymmetric (Figure 11) wave arrival times are calculated to predict the Time of Arrival (TOA) of each wave mode at the primary excitation frequency. The velocities are not only dependent on the frequency of excitation but are also a function of the thickness of the plate. The Lamb wave modes defines the properties of the Lamb waves in the material. In an elastic plate, the symmetric modes of Lamb waves cause particles of the plate to move in opposite directions of the thickness of the plate (Shin and Beckett, 2011).

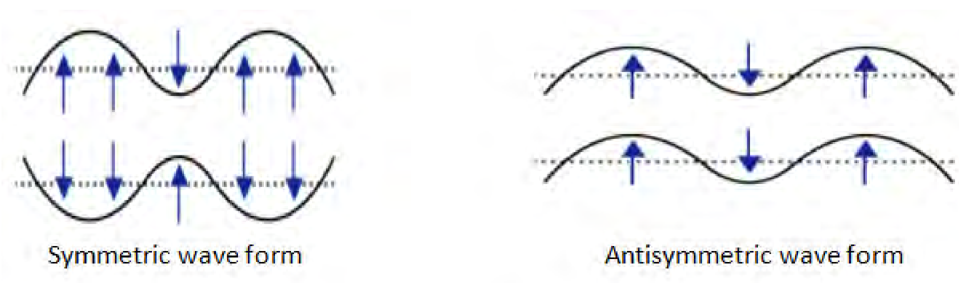



Figure 11: Symmetric (left) and Antisymmetric (right) waves forms

For these lamb waves, multiple waves (or modes) are generated in the material simultaneously, which causes signals to be complex: multiple waves and multiple wave speeds affect arrival times for signals. More extensive descriptions of Lamb waves and their uses are available in other publications, including [9, 16, 28, and 44].

Piezoelectric transducers are the most widely used sensors for damage detection based on sound and ultrasound (see Figure 12).

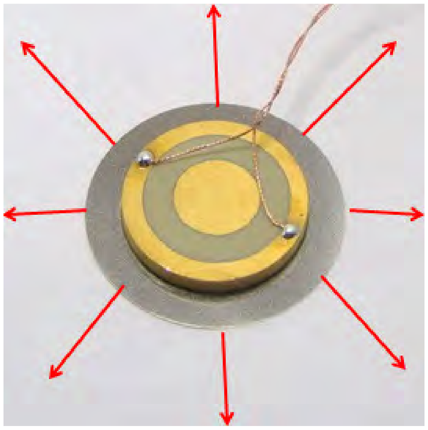


Figure 12: Omni-directional Piezoelectric Transducer

Piezoelectricity is an electric polarization effect due to mechanical forces. In other words, an electric charge is collected on the surface of the piezoelectric material when it is squeezed. Often the converse effect is possible, i.e. the material generates a mechanical strain in response to the applied electric field (Staszewski).

The basic mode of operation is a pitch-catch signal generation and capture. Signal degradation or reflection indicates damage. Many materials have been found to possess piezoelectric properties, but today the most popular material is Lead Zirconate Titanate, (PZT). PZT is cost effective to produce, with higher operating temperatures and greater sensitivity than other piezoelectric materials [33]. PZTs are considered a smart material in the field of SHM, meaning they are capable of both actuating and measuring signals (Adams, 2007).

PZT wafers are constructed with positively charged metal ions, such as titanium, and negatively charged ions, such as lead, mixed in powder form with oxygen molecules in specific proportions. Under the appropriate conditions, the mixed powder is heated and then combined with a binder to form the desired shape (Underwood, 2008).

A PZT wafer may exhibit a non-linear behavior and hysteresis under large strains/voltages or at high temperatures; meanwhile, weak driving force/displacement and brittleness may also narrow its application domain (Su, 2009).

Figure 13: Common PZT Discs Used for SHM [34]

### *2.5.3 Interdigital Transducer IDT*

An IDT is a device that consists of two interlocking comb-shaped metallic coatings (in the fashion of a zipper) which are applied to a piezoelectric substrate, such as quartz or lithium niobate. IDTs are primarily used to convert microwaves to surface acoustic waves (SAW) or Rayleigh Waves.

Lord Rayleigh first explained the Rayleigh Waves in 1885. He described the surface acoustic mode of propagation and predicted its properties. These waves have a longitudinal and a vertical shear component that can couple with any media in contact with the surface. This coupling strongly affects the amplitude and velocity of the wave, allowing SAW sensors to directly sense mass and mechanical properties.

Rayleigh waves can propagate much longer distances with lower signal attenuation levels, which are nominally proportional to $1/r$ for a given frequency (r=distance). In addition to the small attenuation, Rayleigh waves are also non-dispersive and sensitive to surface-breaking defects. The surface penetration depth of Rayleigh waves is also approximately one wavelength, which can be beneficial for many NDT applications. However, one major drawback of using Rayleigh waves for nondestructive testing has been the difficulty of generating Rayleigh waves, where the most commonly used method involves the combination of a plastic wedge and a conventional longitudinal mode transducer (Na, 2008).

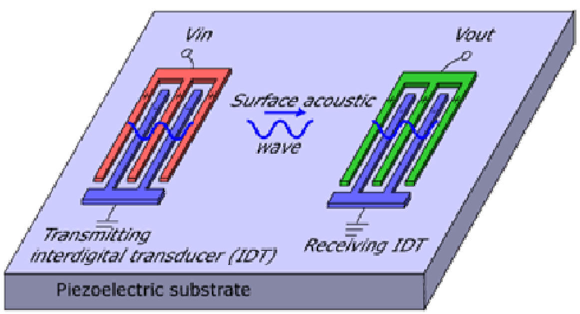



Figure 14: Schematic picture of a simple SAW device (Meltaus, 2009)

Because IDT sensors operate at a single frequency, there will only be one wave speed used to calculate the Time of Arrival for the signal. The signals produced are directional, meaning that the signal is aimed towards the anticipated damage or crack location. The directionality virtually eliminates reflected wave interference and allows the user to place the sensors in a “hot spot” location where predicted damage or crack initiation can occur (Shin and Beckett, 2011).

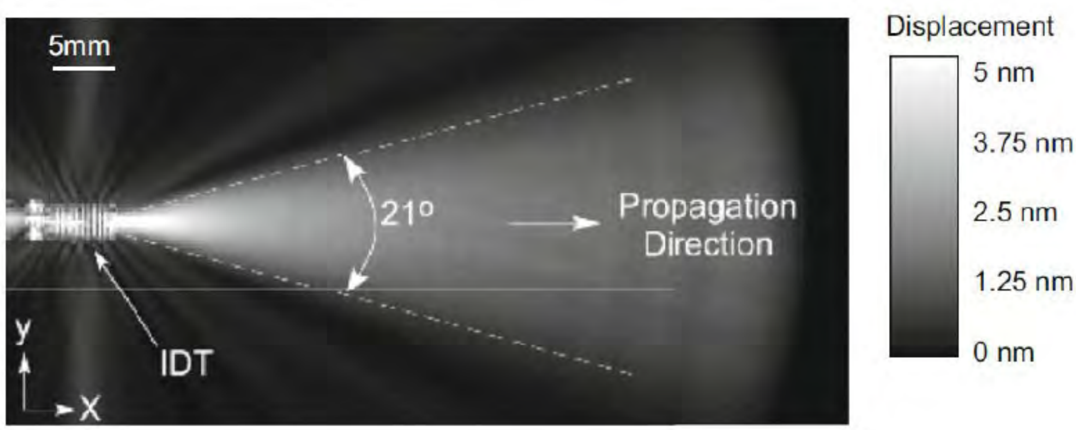



Figure 15: Propagation of Rayleigh Waves from IDT Sensor Showing Directionality (Na and Blackshire, 2009).

Another benefit of IDT sensors and Rayleigh waves is that the pitch-catch signal change linearly with increasing crack length, which provided a new capability for accurately sizing the cracks based on signal strengths in a simple linear manner. This is a foundation for carrying out this research. The more accurately a crack can be characterized, the better knowledge of the real danger the crack represents. The plots in figure 16 (Na and Blackshire, 2009), show the linearity and predictability of the signal change in pitch catch mode. This property of the signal will greatly reduce the possibility of a false signal.

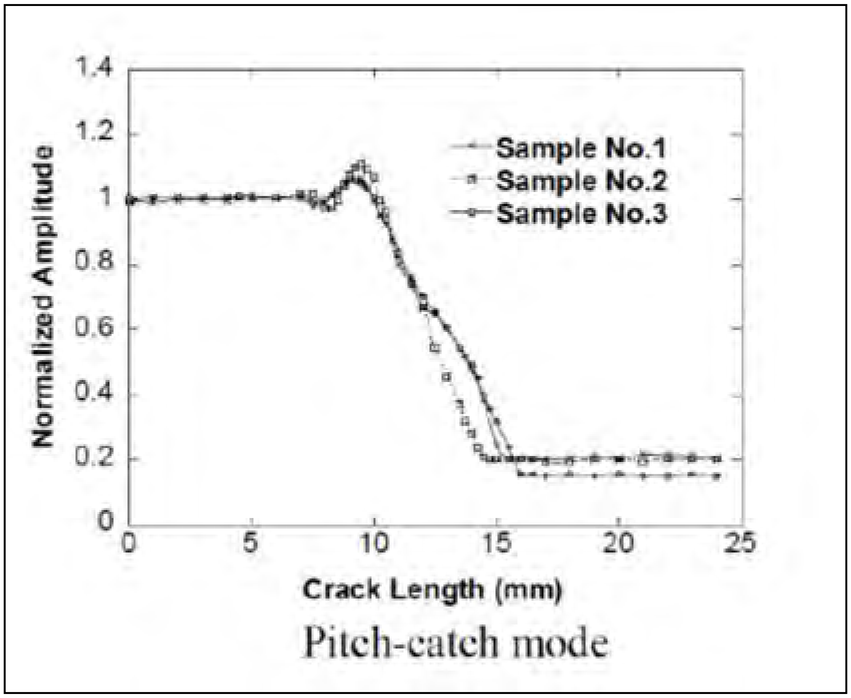



Figure 16: Crack Linearity and Predictability (Na and Blackshire, 2009)

A recent paper summarizes this benefit:

> Figure 16 shows a fatigue crack initiate and grow across the ultrasonic field on a compact tension specimen, both the length of crack and the signals of IDT sensors. In this graph, the amplitudes are normalized to the initial amplitude levels. From the plot in Figure 16, one can notice that there is an indication of the initial interaction of crack tip with the ultrasonic field when the crack length reaches approximately 8 mm which was measured with a micrometer. This indication seems to be composed with two distinctive features of change in the amplitude of signal; a small dip followed by a relatively larger peak. A systematic drop in pitch-catch signal amplitudes to ~20% of the initial levels was noticed (Na and Blackshire, 2009).

### *2.5.4 Probability of Detection and False Calls*

In the research and development stage, the industry has several concerns related to the promising technologies and many questions must be answered before a successful

ISHM system can be implemented. For example, will the sensors report errors? One type of error, known as an $\alpha$ error or a false positive, represents the rejection of the null hypothesis when it is in fact true. In the case of structural health monitoring, an example of this error would be if a sensor reports that a crack has been detected in a critical structural location or that an existing crack has reached critical crack length when in fact a crack does not exist or has not reached the critical crack length. This would result in undue maintenance actions, which is what the ISHM is trying to reduce. A second type of error, known as a $\beta$ error or a false negative, represents the failure to reject a null hypothesis when the alternative hypothesis is true. In the case of structural health monitoring, this error occurs if a crack develops and a sensor fails to report it. The intent of in-situ structural health monitoring is to relieve burdening NDI inspections. If this type of error occurs, the crack may not be known until a critical failure occurs. This is the worst-case scenario for an ISHM (Brown and Hanson, 2008). The detection capability of an ISHM system involves the concept of probability of detection (POD) which describes how well a sensor will detect a crack of a certain size.

Through the use of in-situ ultrasound experiments with PZT and IDT sensors, and applying the procedures suggested here, there will be a reduced risk of false or no reporting crack detection while quickly, routinely, and remotely assessing the integrity of a structure with high reliability. One of the most important benefits of this approach is the augmentation of the POD because, as discussed earlier, the ultrasound waves typically detect cracks based on *effective* and not on *real* crack lengths.

## *2.6 Systems Engineering Approach*

As defined by the International Council on Systems Engineering (INCOSE), a Systems Engineering (SE) approach is:

> *"An interacting combination of elements to accomplish a defined objective. These include hardware, software, firmware, people, information, techniques, facilities, services and other support elements"*

This research considers with a high degree of confidence that the overall ISHM process can be improved using the currently developed technologies, integrating some already deployed systems and components and –in a minor proportion- developing some new capabilities. The review begins with a discussion of pertinent ISHM policies, followed by the description of some programs and assessment procedures, and finally, an identification of the stakeholders, system capabilities, system level requirements and inspection level requirements.

### *2.6.1 Topics of Commercial and Military ASIP Policies*

After the Aloha Accident, the public concerns increased and the United States Congress passed legislation known as the Aviation Safety Research Act of 1988. As a result of the Act and concerns relating to the increasing age of the air carrier fleet, the FAA developed the National Aging Aircraft Research Program (NAARP) to ensure the structural integrity of high-time, high-cycle airplanes. The NAARP structural integrity program area includes three major elements: methodologies to assess the effects of widespread fatigue damage to airframe structural integrity, a damage tolerance analysis

(DTA)-based supplemental inspection program for commuter airplanes, and DTA-based airframe repair assessment.

Due to the increased utilization of the aircrafts, longer operational lives and the high safety demands, the Supplemental Inspection Programs (SIP) were established to provide this level of safety in the large segment of the transport industry [14].

#### *2.6.1.1 FAA Policies*

The FAA has been evolving in accordance with the risks associated with MSD and WFD. As a result, the FAA issued the Repair Assessment for Pressurized Fuselages Advisory Circular that required all airplanes operated under CFR Parts 91, 121, 125, all U.S.-registered multiengine airplanes operated under Part 129, and all multiengine airplanes used in scheduled operations conducted under Part 135 to undergo inspections after their 14th year in service to ensure their structural integrity.

> "…This action is the result of concern for the continued operational safety of airplanes that are approaching or have exceeded their design service goal…"

The proposed rule would also require that damage tolerance (DT)-based SIPs be developed for these airplanes before specific deadlines. This proposal represents a critical step toward compliance with the Aging Aircraft Safety Act of 1991. It ensures the continuing airworthiness of aging airplanes by applying modern DT analysis and inspection techniques to older airplane structures that were certificated before such techniques were available [14].

In addition to this initiative, the AC 91-82 provides the guidance on developing and implementing a Fatigue Management Program (FMP) for metallic fatigue critical structure that includes the damage-tolerance based inspections or a part replacement/modification program to mitigate the demonstrated risks. [13]

#### *2.6.1.2 USAF Aircraft Structural Integrity Initiatives*

In response to the emerging threads and consistently with the commercial aviation initiatives, for nearly 50 years, the United States Air Force has used the Aircraft Structural Integrity Program (ASIP). The Department of Defense issued the MIL-HDBK-6870 [11], Inspection Program Requirements Nondestructive for Aircraft and Missile Materials and Parts that provides the general guidelines to establish a NDE program for the aircraft and missiles including the acceptable NDE processes, procedures and personal training requirements. To *ensure the desired level of structural safety, performance, durability, and supportability with the least possible economic burden throughout the aircraft's design service life* the USAF issued the MIL-STD-1530C [10, 26]. Generally, the ASIP requires tests and analyses to identify critical structural components, determine if these components may fail before reaching the aircraft's design service life, and establish inspection intervals for these components to ensure flight safety (Kuhn, 2009).

The guidance only handbook MIL-HDBK-1823 includes methods for testing and evaluation, as well as procedures for assessing Non-Destructive Evaluation (NDE) system capability contained within specific procedures for conducting the NDI tasks [11].

### *2.6.2 Aircraft Maintenance Strategies*

Current maintenance trends call for the high-speed, low time, highly efficient procedures. Enterprise concepts such as Lean Management and AFSO21 strive for the maximization of the available resources. Aircraft downtime due to maintenance and inspection reduction is the focus of the most recent decade efforts.

#### *2.6.2.1 High Velocity Maintenance*

The High Velocity Maintenance (HVM) program represents a dramatic change in aircraft maintenance, and is seen as a *Maintenance Lean Transformation* because it employs a mixture of productivity and quality enhancement tools derived from Lean, Six Sigma and the Theory of Constraints in pursuit of reduction of time that an aircraft is down at depot. This practice enables more efficient maintenance through a better advanced knowledge of aircraft condition and maintenance tasks to be accomplished. When aircraft come in for an HVM cycle, there is available an increased insight into the aircraft's condition before arrival; lead time for ordering parts and equipment, aligning funding, manpower and engineering support; and flexibility to defer non-safety-critical maintenance. This approach also maximizes the use of parts, materials, tools and information for the mechanics at the point of use, integrated planning and decision making, and more comprehensive data collection. HVM also involves continuous analysis of progress and adjustments of plans to meet goals.

#### *2.6.2.2 Condition Based Maintenance*

Condition based maintenance (CBM) assumes that all equipment will deteriorate and that partial or complete loss of function will occur. CBM monitors the condition or performance of equipment through the use of previous information, feedback, and a variety of sensing technologies. The data is collected, analyzed, trended, and used to project equipment failures. Once the timing of equipment failure is known, action can be taken to prevent or delay failure. In this way, the reliability of the equipment can remain high. This process requires improved processes, technologies, people skills, and communication to integrate all available equipment condition data, such as: diagnostic and performance data; maintenance histories; operator logs; and design data, to make timely decisions about the maintenance requirements of major/critical equipment.

#### *2.6.2.3 Airframe Repair Assessments*

A critical issue identified by the civilian and military aviation industry is the need to examine the effects of repairs on the structural integrity of aircraft. The use of damage tolerance methodologies in the maintenance and repair practices of aircraft is required in order to ensure their continued airworthiness and operational safety. The resources needed for damage tolerance designs of repair are lacking for small operators, independent repair facilities, and military repair depots. In an effort to address this need, a task was undertaken under the joint sponsorship of the USAF and the FAA to develop a new, user-friendly software tool, Repair Assessment Procedure and Integrated Design (RAPID), that performs the static strength and damage tolerance analysis of aircraft fuselage skin repairs. The tool assists the user in assessing mechanically fastened fuselage skin repairs with up to two doublers. The static analysis determines if the doublers and fasteners are statically adequate, and the damage tolerance analysis yields the residual strength, the crack growth life, and the inspection intervals for maintenance schedule of the repair [14]. The tool includes the analysis through the use of static modules, damage tolerance modules, the common repairs and the analysis of procedures through comprehensive flow charts.

### *2.6.3 Fatigue Management System*

Extensive research has been conducted including [2,5,20,44] to lay down the high-level characteristics of an ISHM system. The high-level characteristics of the system are perfectly concordant with this research.

#### *2.6.3.1 Stakeholders Identification*

This research has identified the key stakeholders. Due to its nature and potential capabilities, it includes a wide and diverse group of organizations and people interested in going further and deeper in researching for their specific area.

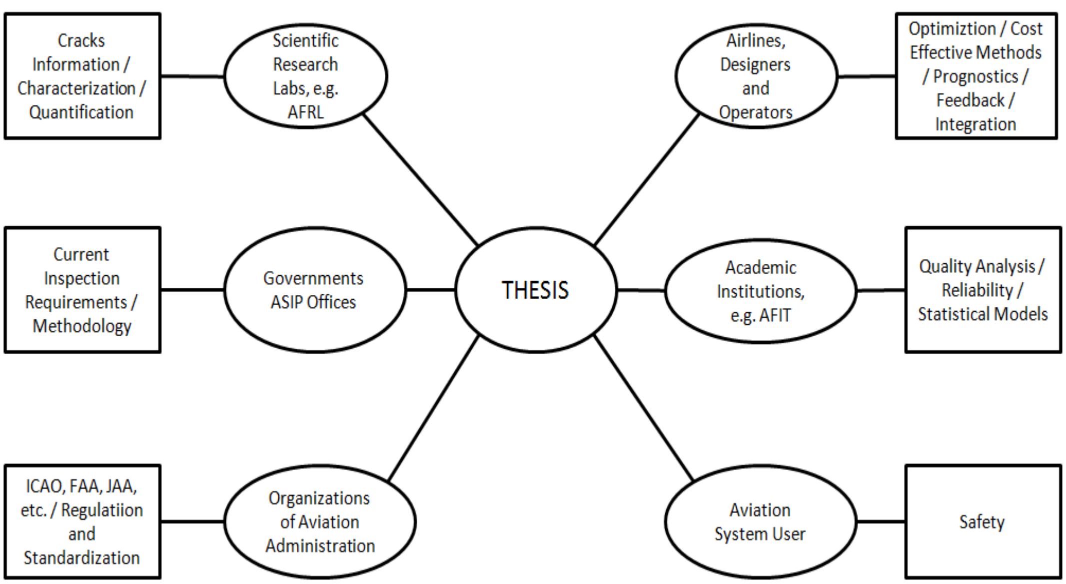



Figure 17: Stakeholders Identification

The scientific research labs, specifically those involved with materials research and nondestructive inspections might be interested in getting a better knowledge of the crack behavior as well as the material loads and ultrasonic wave interaction. The airlines, aircraft designers and operators are interested in developing strategies to optimize the aircraft inspection procedures. This approach to develop the ISHM tasks will minimize the valuable time of the aircraft on-ground. The system is envisioned to be predictive and not responsive or corrective. As a result, information processed through the various operators, designers, technicians, etc can be shared in the "ultrasonic wave language". As discussed in this chapter the aircraft fleet numbers are diminishing and assets are aging. The government ASIP offices and the Organizations of Aviation Administration can find in this research an alternative to provide the guidance to handle this imminent scenario.

It is highly recommended to establish global standardized NDI and ISHM procedures to facilitate their integration capabilities. By performing real time ultrasound structural health monitoring, it should be possible to generate a complete signal repository with a great level of detail.

The academic institutions can find in this approach, an opportunity to set down the idealized baselines for different crack sizes by using computer-based tools, and to develop statistical models and methods to determine the disposition of the sensors in the structure, the location of those sensors, the amount of sensors required for a specific structure, the lifecycle cost associated with SHM tasks, error types probability of detection, false call rates, Analysis of Variance (ANOVA), etc.

Finally, the main concern when a customer boards an airplane is his/her SAFETY. A highly probable crack detection system ends up being a safer flight transportation and operation service.

#### *2.6.3.2 System Capabilities*

Brown and Hansen [5] identified four capability gaps relating to the current inspection paradigm for the USAF but expandable to the aviation industry as well. The capability gaps included:

1. *Reduce Sustainment Effort*: The current methods involve manual inspections, which are not cost-effective and do not truly embody the right support, right place, right time, in the right quantities concept, but are preventative measures.
2. *Facilitate Informative Decision-Making*: Current methods do not meet the Focused Logistics [goal] as being a real-time, net-centric system providing asset visibility. Assets are only visible while grounded, during inspection periods.
3. *Maintain Situational Awareness*: Current methods do not have a robust network of sensors and thus are not capable of monitoring and tracking assets, at least not in the structural sense. This information could be used by others to increase overall situational awareness.
4. *Assess Performance and Implementation Improvements*: Data capture and analysis is critical to successful redesigns and future designs. Currently, data is only captured during inspections and not while in-flight. Without in-flight data capture, flight loading analysis can only be accomplished during operational testing.

#### *2.6.3.3 System Level Requirements*

Previous work by Kuhn [20] identified and summarized the system level requirements to characterize the specific aircraft structural analysis. See table 1

**Table 1: System-level requirements for a SHM system [20]**

| Requirements | Reference(s) |
|---|---|
| Data easily downloadable from aircraft | 18 |
| Data compatible with existing infrastructure | 18 |
| Quickly sort large amounts of data for critical information | 6 |
| Software handles, stores and interprets large amounts of data | 18 |
| Easy to replace sensors | 3 |
| Signal processing can compensate for slight sensors misalignments | 3 |
| Software handles high and low term structural issues | 45 |
| Address both real time and long term structural issues | 19,27 |
| Ease of maintenance and installation | 19 |
| Redundancy and fail safe operation | 19 |

#### *2.6.3.4 Inspection Level Requirements*

The general needs identified to carry out the fuselage inspection must be established. This sets up the baseline when assessing the specific detection process.

a) *Procedures are non destructive in nature*: The damage or permanent deformation of elements while performing the inspection process is inadmissible.

b) *De-emphasis on the human factor and technique*: Current detection techniques rely heavily on human abilities and experience. The operator/inspector experience and skills determine, to a large degree, the success or failure in applying the procedure. The proverbial "needle in a haystack" applies when *searching for a crack quite possibly the size of a needle in an area one-sixth to one half the size of a football field.*

c) *Fast, no more than 24 hours for a complete fuselage inspection:* This is the current standard time to perform this activity. Time varies according to the aircraft. This requirement can be complemented or fulfilled by applying real-time detection procedures.

d) *Utilization of concepts and technology to reverse the heavy bias for missing a crack to a strong bias for finding a crack:* The general process suggested by this research represents an extraordinary source of focus to increase the probability of cracks detection.

e) *Possibility to record:* Data such as strain, temperature, loads, moisture, etc. must be recorded for their analysis as contributing factors.

### *2.7 Previous Research and Related Developments*

In this section, there is summarized some relevant research and developments which support the feasibility of the procedures here proposed.

#### *2.7.1 The Growth of Small Cracks in Airframe Structure*

In this paper published in the Third Engineering Foundation International Conference in December 1998, Robert S. Piascik [32] carried out a series of experiments to analyze the presence of small fatigue cracks contained in hundreds of rivet holes resulted from fretting damage along the mating surface of the riveted lap joint. The formation of microcracks within the fretting region led to the development of small fatigue cracks that were undetected during the major portion of the full-scale fuselage fatigue test (60,000 full pressure cycles). In this research, destructive examination of three full scale aluminum fuselage panels was performed and it was discovered that a high proportion of each section was fatigued and small cracks existed in the riveted fuselage skin exhibit similar fatigue crack growth characteristics with dimensions between 50 µm and 10mm (Figure 18).

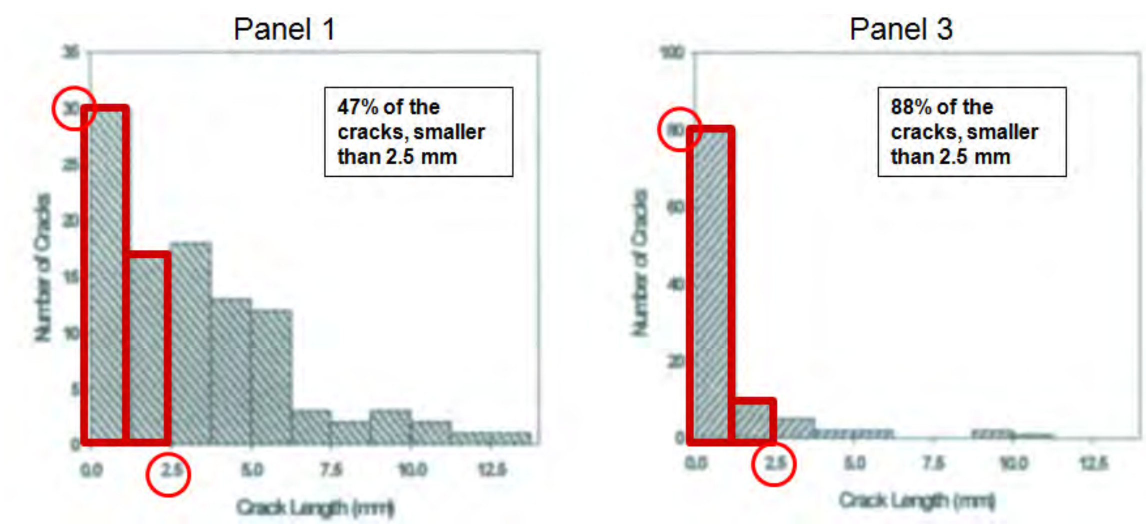



Figure 18: Outer Skin Fatigue Crack Length Distribution [32].

Figure 18 shows the cracks distribution according to their size in the two reported panels. It can be seen that a very high proportion -47% and 88% respectively- of those cracks were smaller than 2.5 mm of length. It seems to be obvious that the crack detection goals should be established consistent with those levels. For example, in the panel number 3, detecting one 10 mm long crack could mean that 98% of the real cracks are not being detected or are undersized. In addition, it demonstrates as well, that generally there is not one single fatigue crack but MSD. Usually fatigue cracks develop in a wide area, which individually are not dangerous, but collectively are dangerous.

Being focused on detecting small-size cracks will enable the early corrective procedures and will decrease the probability of undesired events.

### *2.7.2 Method of Testing for Fuselage Cracks*

In this paper reported by W. Craig Willian [8], the author describes experiments in which several aircraft fuselages were successfully pressurized on the ground within a variety of pressures ranging from 5 psi to 14 psi. This research is relevant for this thesis because, even though his approach to detect cracks is different from the process proposed in this research, tests were conducted using ground pressurization cycles. What is considered relevant for this report is the feasibility to manipulate the cabin pressurization for detection purposes during maintenance procedures. This was an assumption at the first stages of this thesis and was found in the literature to support this assumption.

### *2.7.3 Real-Time Aircraft Health Monitoring*

AIRMAN (AIRcraft Maintenance ANalysis) is an intelligent application developed recently by Airbus to optimize the maintenance of aircraft. This software constantly monitors the health of an operator's jetliner, and instantly advises if a fault or warning message is registered through its on-board maintenance system. All information is collected automatically and transmitted to ground control via the aircraft's communication system.

In addition to advising operators of technical problems, AIRMAN also provides access to the necessary information for resolving these situations quickly and efficiently with a single centralized interface screen.

AIRMAN is able to reduce troubleshooting time due to its advanced capabilities, allowing for early notification of aircraft events and rapid access to relevant documentation, while delivering details on the aircraft's maintenance history and information on previous maintenance work performed.

The AIRMAN utility fully-leverages Airbus' manufacturing expertise and in-service experience to provide on-target troubleshooting steps, which are prioritized to ensure that its first recommended task has the highest probability of rectifying the situation.

A key component of this maintenance system is Airbus' AIRMAN Repair Manager, which offers airlines a simple method to view and locate external non-conformities, and to record details of internal damage and repairs.

The AIRMAN Repair Manager's objective is to ease structural damage reporting and to reduce the amount of time needed to assess damage and authorize an aircraft's return to service. It allows a significantly faster resolution lead-time, ensuring cost-effective repairs while improving overall aircraft availability.

When damage is identified, a user with valid access to the airline network and AIRMAN-Airline database can report the appropriate information through a guided interface. This delivers the required information for damage evaluation and reports the necessary data to the airline Maintenance Control Centre (MCC) – or Airbus, if further investigation is required [36].

# *III. Experimental Setup and Modeling Studies*

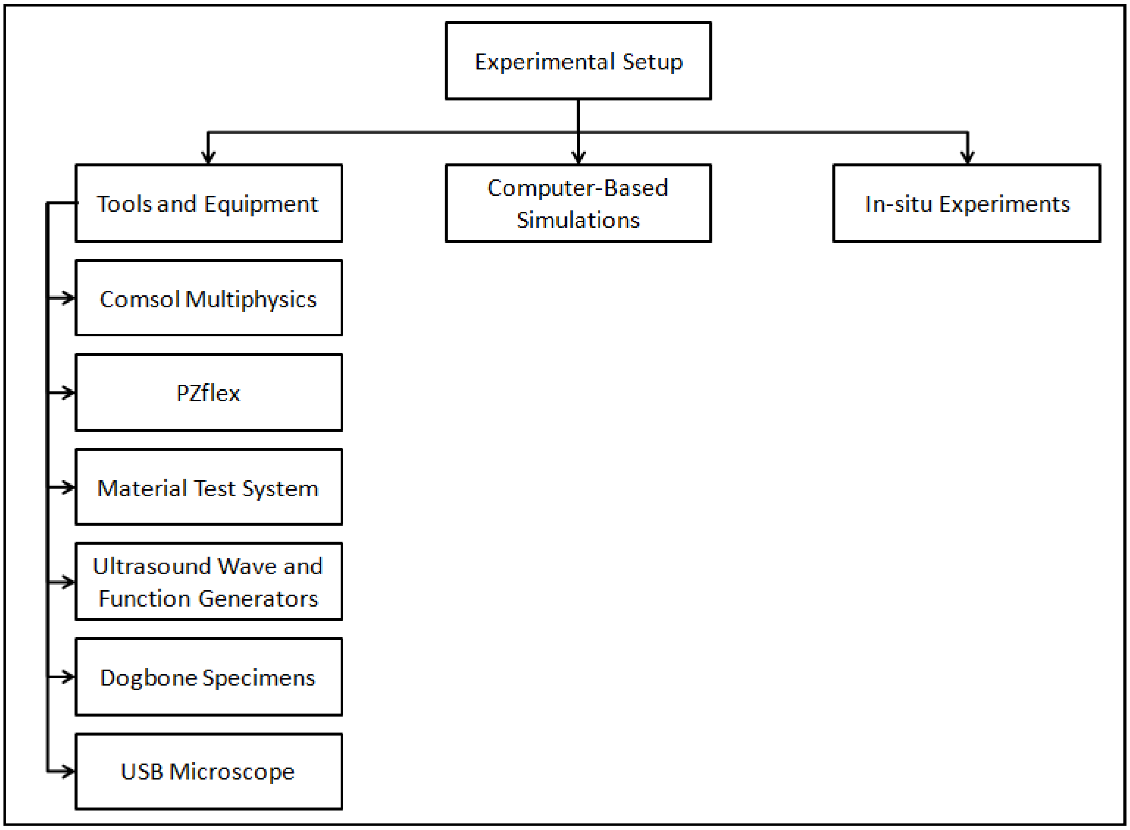



Figure 19: Chapter 3 Decomposition

This chapter (Figure 19) discusses the methodology, set-up and tools used to accomplish this research: In-situ accelerated fatigue testing and camera-based microscopic imaging, Finite Element Modeling Analysis (FEMA) using the Comsol ® software and ultrasonic 2D Wave Propagation Simulation using the PZflex ® software, and in-situ bonded PZT and IDT sensing. Figure 20 depicts the schematic flow of events. First it was required to grow the cracks. These real cracks served as input for the modeling software. Finally, the specimens were placed in the MTS load frame again but now to perform the ultrasound sensing and in-situ microscope imaging upon a controlled load application process.

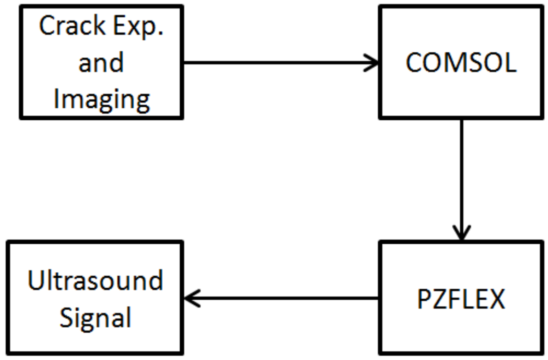



Figure 20: Research Schematic Diagram

By using this approach, it is possible to determine how consistent the simulated and experimental results are with those analytical theories discussed in sections 2.4 and 2.5. The goal of this step in the research is to determine how predictable the REAL behavior of a small single edge crack is when a load –such as pressurization- is applied. By using modeling tools, it is possible to change the testing conditions to perform as many experiments as required to follow or imitate through a *simplified* description -especially a mathematical one-, a system or process, to *assist calculations and predictions.* By doing experimental testing, it is possible to observe the behavior of the real crack while applying a controlled load.

### *3.1 Tools and Equipment*

#### *3.1.1 Comsol Multiphysics*

COMSOL Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems. With this software, it is possible to easily extend conventional models for one type of physics into multiphysics models that solve coupled physics phenomena—and do so simultaneously. Using the built-in physics interfaces and the advanced support for material properties, it is possible to build models by defining the relevant physical quantities—such as material properties, loads, constraints, sources, and fluxes—rather than by defining the underlying equations. It is always possible to apply these variables, expressions, or numbers directly to solid and fluid domains, boundaries, edges, and points independently of the computational mesh. COMSOL Multiphysics then internally compiles a set of equations representing the entire model. The Solid Mechanics interface in the Structural Mechanics Module provides the features to interact in the following space dimensions: 3D solid, 2D plane stress, 2D plane strain and axisymmetric solids (Comsol AB, 2010)

### *3.1.2 PZflex*

PZflex is a computer-based tool specialized in virtual prototyping of large wave propagation problems, with emphasis on featuring electro-mechanical materials. It allows toggling between 2D and 3D space to see how the object interacts with the details grid. This software has been adopted by all the major ultrasound imaging manufacturers in the world and has expanded into a wide range of markets—actuators, sensors, telecommunications, nondestructive testing, and others. The common link among these markets being piezoelectric and ultrasound wave propagation (Raynolds, 2009).

### *3.1.3 Material Test System*

One four posts servo-hydraulic Material Test System (MTS) with capability to deliver controlled cyclic and static tension and compression loads up to 20 kips was used for both the accelerated fatigue testing and the tensile load application.

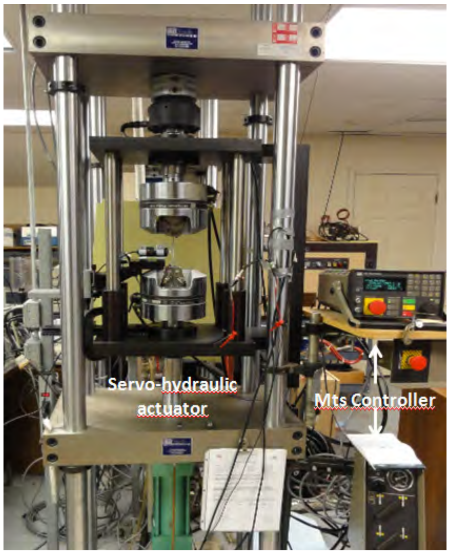



Figure 21: MTS Machine

### *3.1.4 Ultrasound Wave and Function Generator*

The LeCroy Waverunner LT584 is a digital standard four channel oscilloscope able to provide 1 GHz of bandwidth at 2 GS/s into 250 kpts of acquisition memory per channel. It can also be equipped with 4 Mpt memory (8 Mpts in 2-channel mode), along with 4 GS/s sample rate in 2-channel mode. This allows single-shot capture of long, complex signals at high sampling rates. There is an external trigger input which can be used to trigger on an additional signal [21].

The Agilent 33250A device is a function, arbitrary waveform, and pulse generator in one instrument with very stable frequencies featuring 80 MHz bandwidth with low distortion.  The system provides AM, FM, and FSK modulation capabilities, sweep and burst modes, and color graphic display.

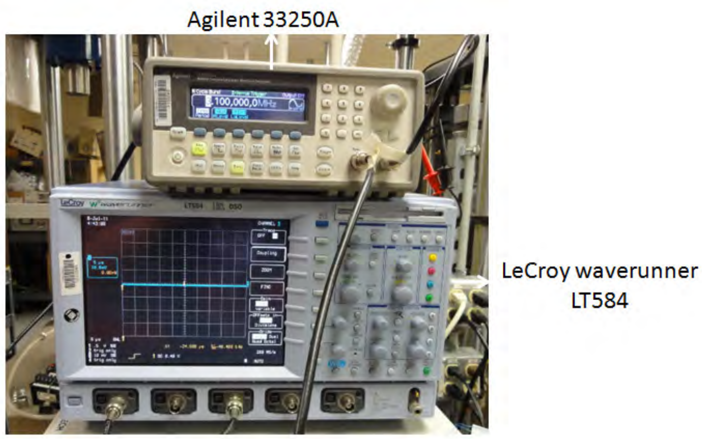



Figure 22: Function and Wave Generator

### *3.1.5 Dogbone Specimens*

This research used six 142 x 32 x 6mm x 1mm thick aluminum 2024-T3 notched dogbone specimens, which were subjected to accelerated fatigue testing and sensors were bonded as shown in figure 23 and figure 24.  Because of the complexity of the accelerated fatigue testing and the small transversal area, three samples failed while growing small cracks.

Figure 23: Dogbone Specimen

Figure 24: Bonded Sensors on Dogbone Specimens

The most important properties of the dogbone aluminum specimens material are summarized in table 2.

**Table 2: Aluminum 2024-T3 Properties**

| Material | Property | Amount | Unit |
|---|---|---|---|
| Aluminum 2024-T3 | Density | 2770 | kg/m3 |
| | Elastic Modulus | 7.31E+10 | Pa |
| | Heat Capacity | 963 | J/kg*°C |
| | Poisson's ratio | 0.33 | |
| | Thermal Conductivity | 190.4 | W/m*°C |
| | Thermal Expansion Coefficient | 22.68 | µm/m*°C |

### *3.1.6 USB Microscope*

The Global Sound International GZX400XBK high-definition scientific digital LED microscope (Figure 25), was used to get images and videos from the specimens during the accelerated fatigue testing and controlled load experiments.  Due to the complexity of the task, it was identified that the device must have USB video connection features to Computers/Laptops/Notebooks and to magnify the microscopic cracks between 25x to 400x with special image treatment.  The recorded images were used to record their trends and to measure the experimental Crack Opening Displacement (COD).

Figure 25: GSI GZX400XBK Microscope

### *3.2 Computer-Based Simulations*

The modeling phase was performed by taking advantage of the unique capabilities offered by utilizing the combination of COMSOL ® and PZflex®.  Several models were created to reproduce specific simulations.

Initially, in COMSOL ® Multiphysics, we modeled the specimen with exactly the same 3D geometry and characteristics as those described by the aluminum 2024-T3 dogbone specimens (see Figure 26).

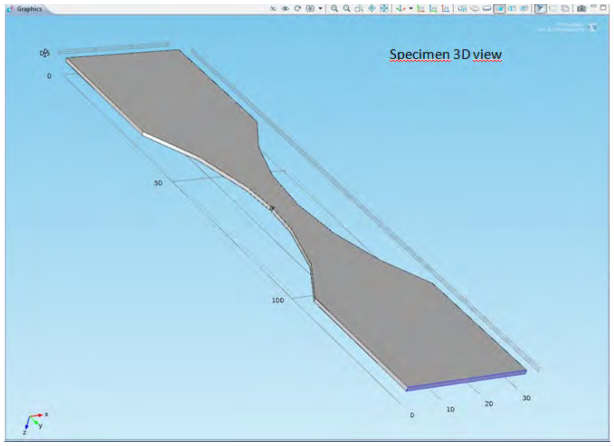



Figure 26: Comsol 3D Aluminum Specimen

As described before, Comsol offers exceptional features to perform the modeling in a variety of scenarios. During this section of the research, these features were widely used to analyze how differences in the configuration would influence the outcome. The modeling results will be discussed in section IV, however, parameters such as mesh geometry, and load application were consistent with the expected results. The experiments are reproducible and the outcome will maintain its quality. This was required because there is no literature about previous usage of software in conducting these specific type of experiments (see Figure 27).

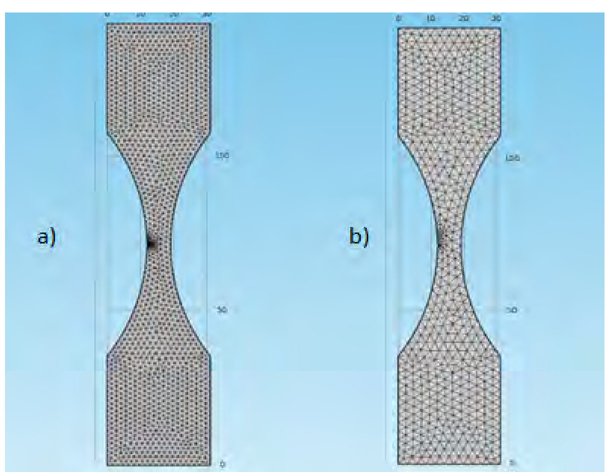



Figure 27: Comsol a) Extra Fine Mesh, and b) Normal Mesh

After testing the suitability of the software for this specific set of computer-based experiments, we conducted the crack analysis. We created models including exactly the same crack length as those observed in the real specimens under Accelerated Fatigue Testing (AFT). Because of the complexity of the real crack which commonly grows through the grain boundary, these models were built assuming simplified linear cracks (see Figure 28).

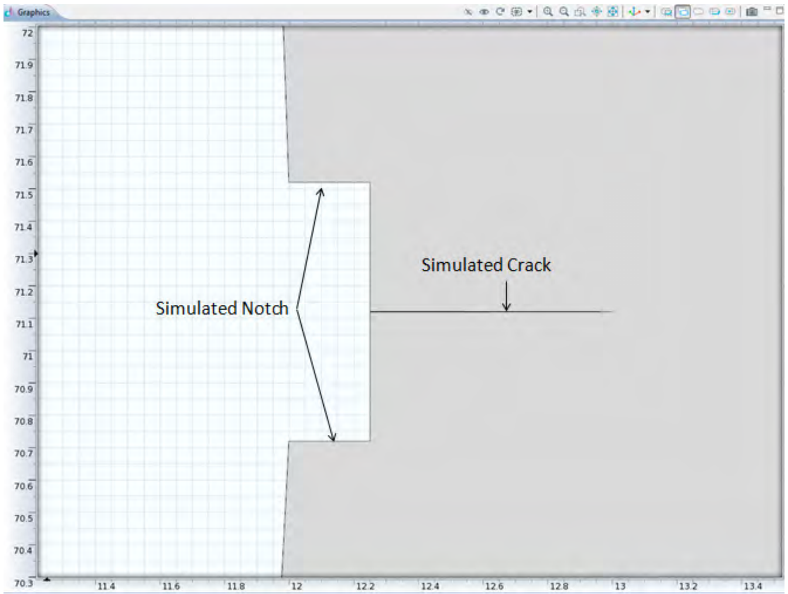



Figure 28: Comsol Idealized Notch and Crack

The last step in this modeling section was applying a variety of loads ranging from 100 lbs to 400 lbs and measuring their individual COD.

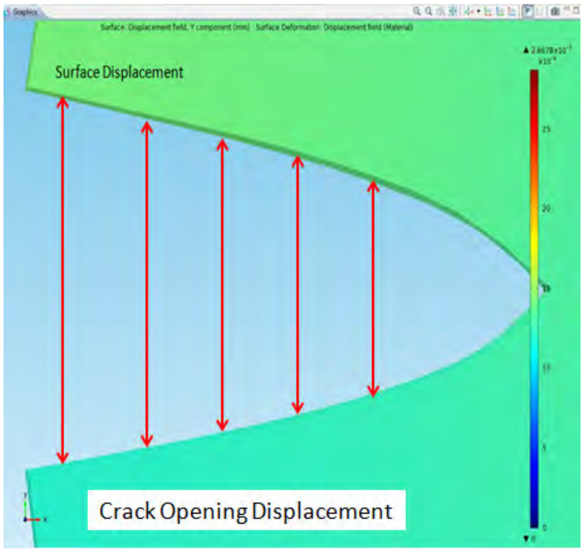



Figure 29: Comsol Crack Opening Displacement (COD)

The outcome is given in a degraded scale of colors. The stress concentration and idealized surface displacement can be analyzed by using those scales (see Figure 29 thru Figure 31).

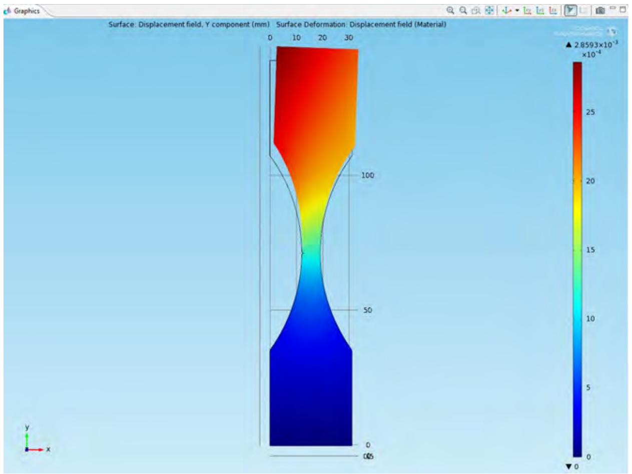


Figure 30: Comsol Surface Displacement

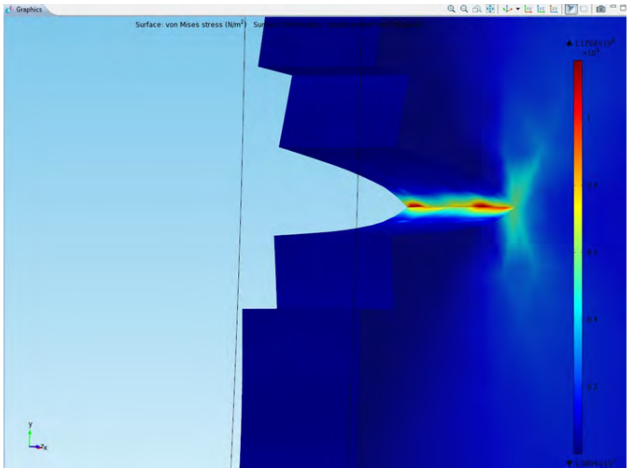


Figure 31: Comsol Stress Concentration

The finite element analysis and the crack opening displacement upon load application were successfully developed by using the capabilities offered by Comsol ®. Now our interest was focused on determining how a model could provide information about the ultrasound wave signal changing upon passing through a crack. The Comsol dog bone model was utilized as the input for PZflex simulations (see Figure 32).

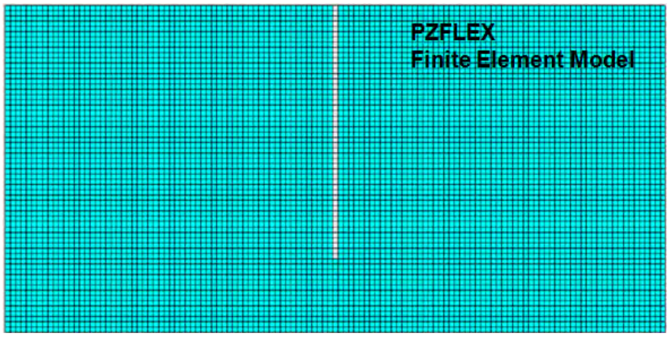



Figure 32: PZflex Finite Element Model

The finite element model was subjected to an idealized 1-cycle pitch-catch sinusoidal 300 KHz to 5 MHz wave in the 2D-plane from left to right. The crack opening behavior was modeled as variation in crack length.

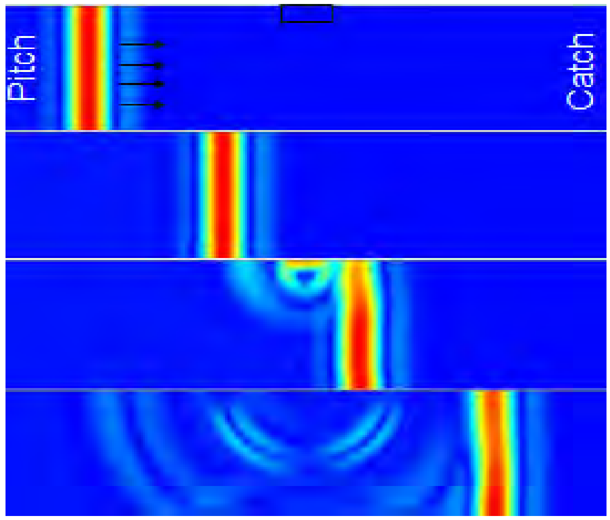



Figure 33: PZflex Wave Propagation

As shown in Figure 33, wave scattering leads to a decrease in the simulated signal level as effective crack length increases due to a tensile load increase. This behavior and trend are very likely to imply that most of the effective crack length is ineffective for wave propagation detection purposes when the two crack faces are touching each other, and the wave is not scattered enough to clearly show a dangerous discontinuity. In Chapter IV this will be discussed further, along with the quantified signal reduction due the simulated growth in the crack length.

### *3.3 In-situ Experiments*

The in-situ experiments were developed in two phases: 1) accelerated fatigue testing and microscope imaging, 2) bonded piezo sensing due to crack opening behavior. Six aluminum 2024-T3 dog bone specimens were tested, where small crack were grown under AFT with the results summarized in table 3.

**Table 3: Crack Growth under AFT**

| Specimen | Nf. Cycles | Max Load (Lbs) | Max Stress (ksi) | Crack Length (um) | Remark |
|---|---|---|---|---|---|
| LS-9 | 76,395 | 936 | 30 | NA | FAILED |
| LT-6 | 675 | 553 | 35 | NA | FAILED |
| LT-8 | 1,733 | 932 | 30 | NA | FAILED |
| LT-10 | 29,407 | 389 | 25 | 750 | CRACKED |
| LT-13 | 15,003 | 396 | 25 | 922 | CRACKED |
| LT-19 | 7,192 | 474 | 30 | 736 | CRACKED |

After the tests, we obtained three specimens with small crack lengths –smaller than two millimeters- and with a non-linear geometry. Real cracks grow in an unpredictable trend that is highly dependent on the material grain structure, the specific mechanical properties, and the loading processes. After the cracks were grown, we took microscopic images and measured their length (see figures 34 thru 36). As stated before, these lengths were the input for the Computer Based models.

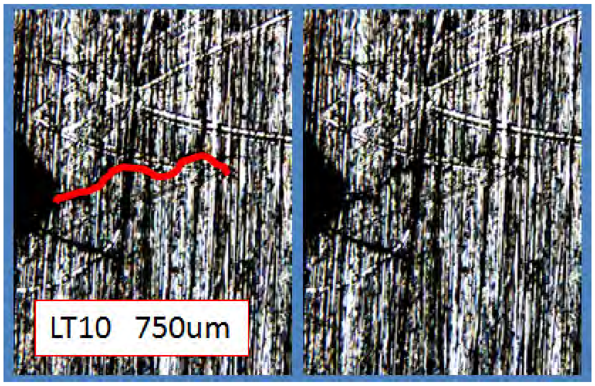



Figure 34: LT-10 Cracked Specimen

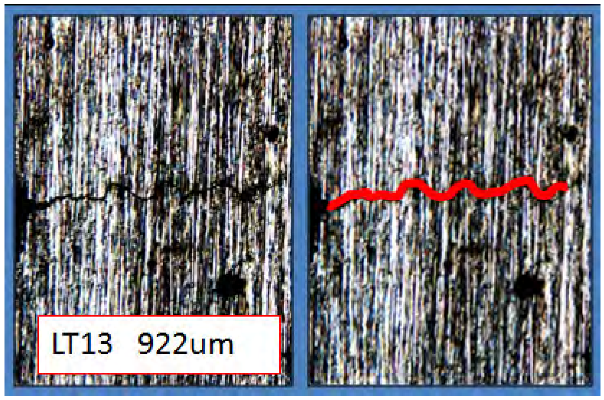



Figure 35: LT-13 Cracked Specimen

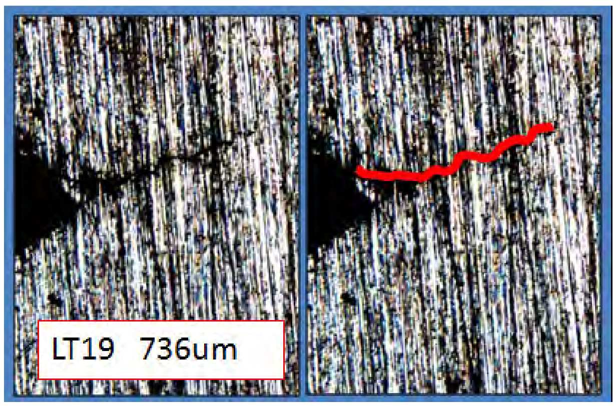



Figure 36: LT-19 Cracked Specimen

After successful completion of the crack growth, imaging and modeling, we bonded IDT sensors on one sample´s face and PZT sensors in the other face (see Figure 37 and Figure 38). One of the most important objectives of this procedure was to research if it is possible to get conclusions by using both omnidirectional (PZT) and directional waves (IDT) and to verify whether those findings were meaningful to be able to state conclusions about the technique regardless of the technology used between PZT and IDT ultrasound sensors.

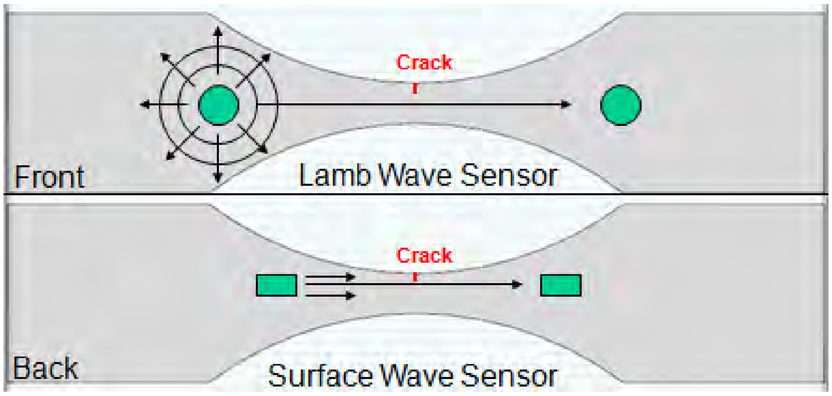



Figure 37: Location of Sensors

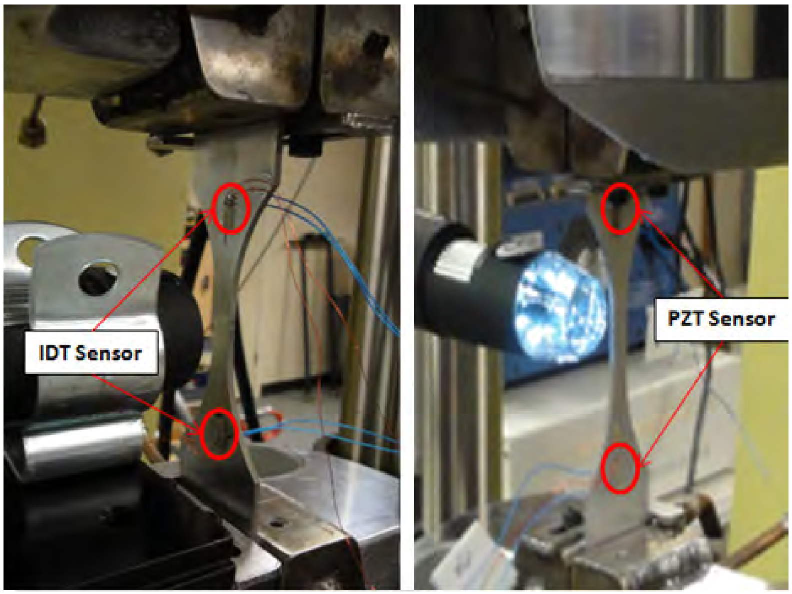



Figure 38: Left: IDT Sensor, Right PZT Sensor

Figure 39 depicts a schematic diagram of the in-situ experimental measurement system with the cracks induced and the sensors installed; a simultaneous three-steps process was conducted to expeditiously (to avoid material creeping) load the specimens at specific stress levels, generate and record ultrasound waves' response, and image the crack behavior.

a) Loading each specimen over the 0 lb to 350 lb range in 50 lb increments (Figure 40),

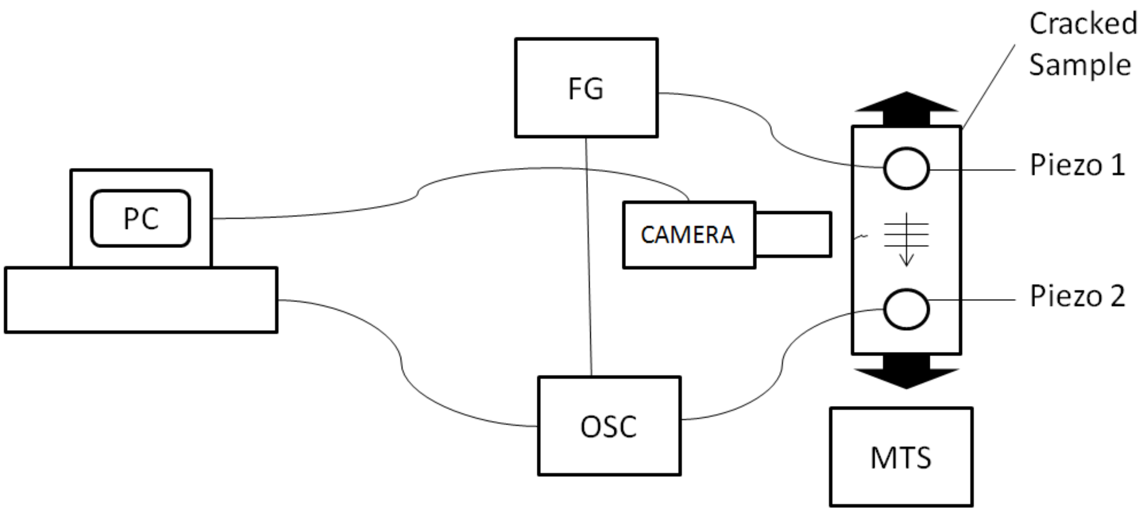



Figure 39: In-Situ Experiments Schematic Diagram

Figure 40: In-Situ Crack Loading and Imaging

b) Pitch-catch sensing by sending a 3.1 MHz sinusoidal tone burst signal, 5 cycles waves or a 100 kHz to 600 kHz in 100 kHz increments, 5 cycles tone burst, omnidirectional wave generated from the function generator and amplified through the power amp to drive the IDT or PZT and recording,

Figure 41: In-Situ Bonded PZT and IDT Sensing

c) Image capturing to measure the crack opening displacement.

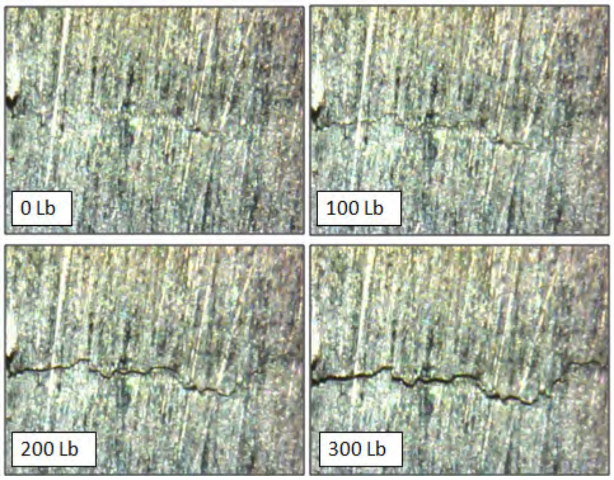



Figure 42: In-Situ Crack Opening Imaging

## *IV. Experimental Results and SE Approach*

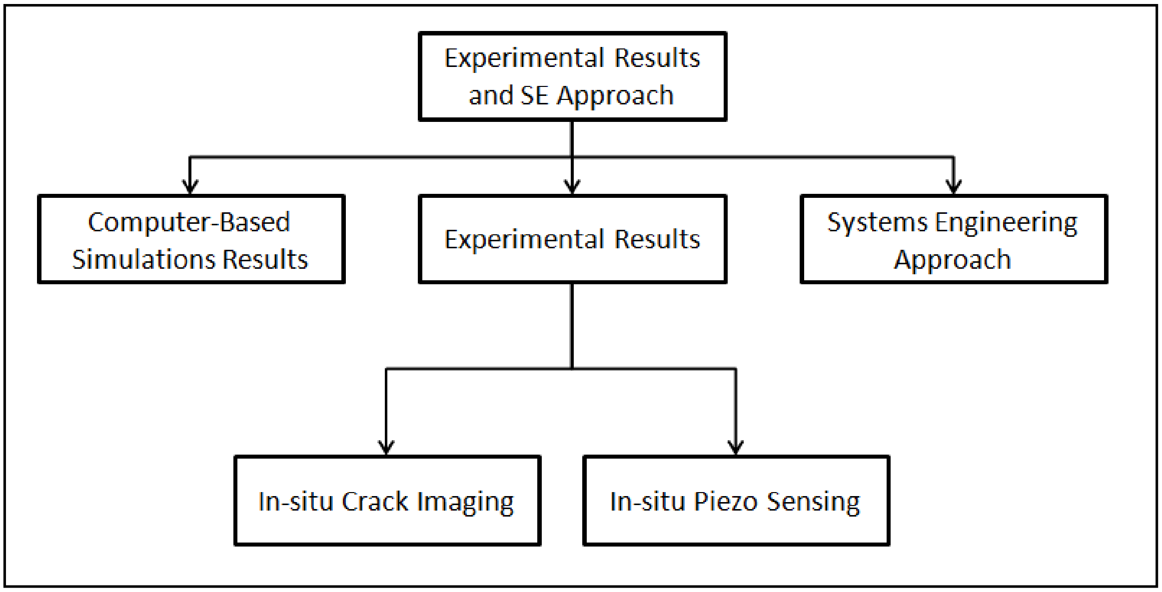



Figure 43: Chapter 4 Decomposition

The goal of this research is to demonstrate a more efficient sequence to apply the sensors-based SHM techniques with the tools available increasing the POD by suggesting a procedure to improve the capability of the current system and to provide some foundation in the scientific knowledge around the cracking behavior and characterization in the non-destructive evaluation field. To accomplish this task model simulations, in-situ experimentation and characterization were performed on three dog bone specimens made of Aluminum 2024-T3 under varied tensile loading levels. A detailed sensing outcome and imaging record was carried out and evaluated. Because of the numerous experimental observations, more than 150 complete sets of data were collected at different stress levels and compared among them; more than 200 images of the cracks were taken and analyzed while monitoring their behavior. There is reported only a relevant and conclusive sample pertaining to a comparison either of the three samples or specifically for the LT19 specimen. The results of the modeling, experiments and the proposed systems engineering approach are discussed in this chapter.

### *4.1 Computer-Based Simulations Results*

The purpose of using the Computer Model tools was to evaluate the consistency of the modeling used in defining crack characteristics such as the COD and the maximum crack opening displacement upon loading. The three cracked specimens that were modeled showed very consistent trends. In figure 44, the maximum crack opening displacement at different loads is plotted. The model assumes that there is no crack growth upon load application. The goodness-of fit given by the scatter diagram was $R^2 = 1$ for the three specimens. A series of verification simulations were carried out with different cracks sizes yielding the same results. The usefulness of this section of the research allows us to conclude that by modeling cracks, it is possible to determine a linear equation based on the crack length. Once the idealized line equation is determined, it is possible to determine the expected tip opening displacement upon load application for detection purposes. The models have the capability to provide a starter point to establish the theoretical baseline.

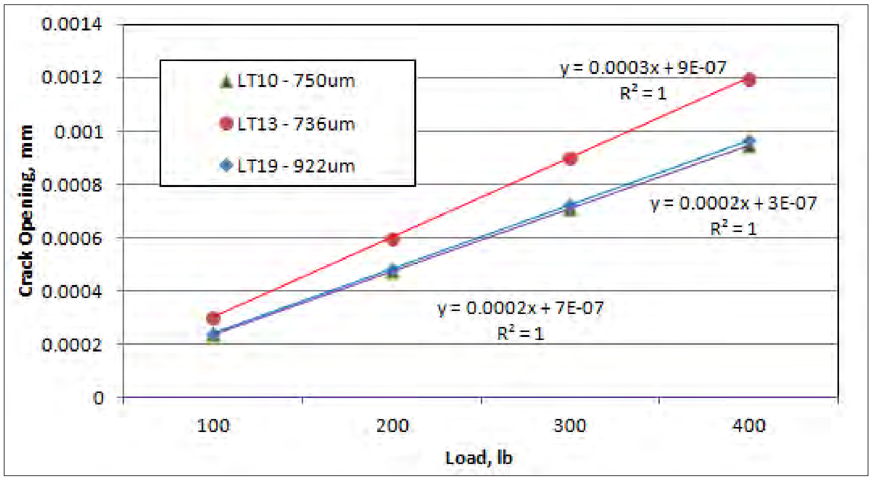



Figure 44: Idealized Crack Opening vs Load

The next step was to measure the COD in eight pairs of adjacent crack points upon load application. As pointed out before, when there is no load, the plastic region closes to the crack tip due to compressive stresses, pressing the crack faces together and "hiding" the crack. We are interested in assessing how a crack behaves at different stress levels. After analyzing the outcome, a consistent logarithmic behavior might be expected. If we are able to determine the crack length and the load to be applied, it should be possible to determine the local COD and the effective crack lengths (see Figure 45).

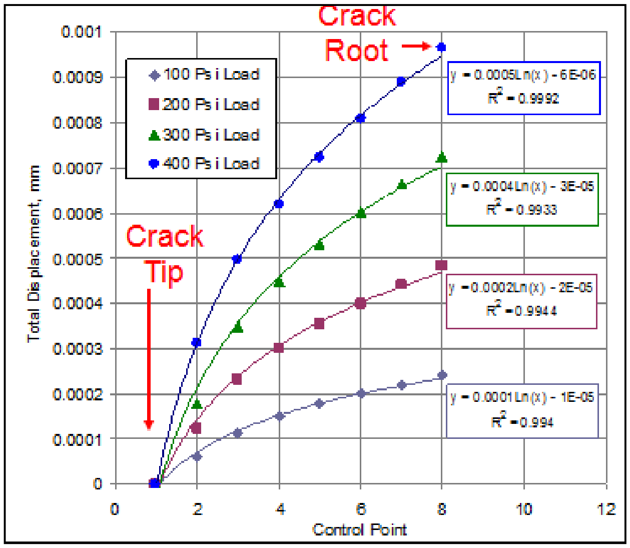



Figure 45: Logarithmic Crack Opening Behavior

After a Finite Element Analysis was performed and recorded its results for the idealized linear crack, the COMSOL model output was used as the PZflex input. An idealized pitch-catch wave from left to right was simulated and a noticeable signal scattering after passing the crack was identified as a variation in the wave amplitude (figure 46).

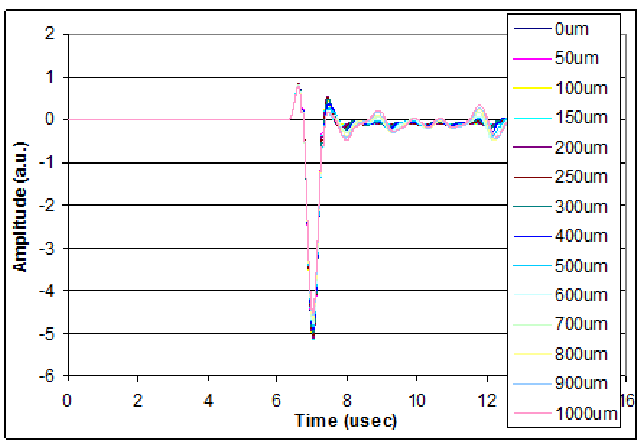



Figure 46: PZflex Pitch-Catch Signal from Right Side

To be consistent with the FEA model, the signal level decrease as the effective crack length increased was investigated. In figure 47, a nearly linear decrease is observed in the simulated signal level as effective crack length increased.  When a load is applied (tensile load increases) the effective crack length increases and in some –possibly measurable proportion-, the ultrasonic wave scatters at a predictable rate.

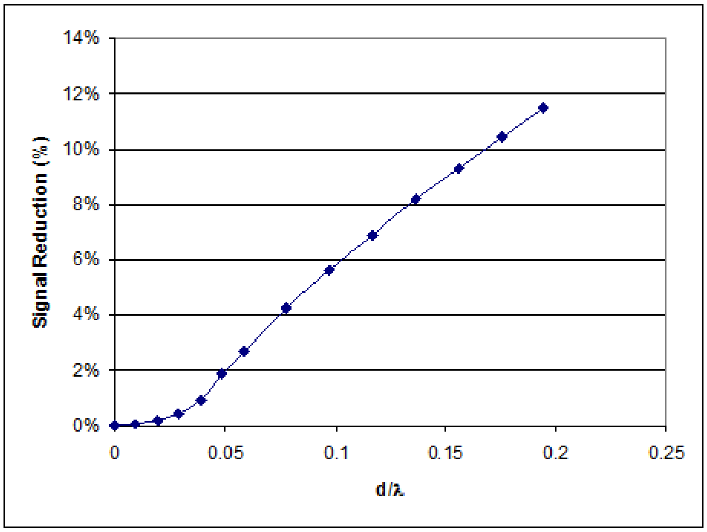



Figure 47:  Ultrasonic Signal Reduction vs. Effective Crack Length

The use of ultrasound waves allows the potential capability of recording the monitored results and comparing among fleets to identify the most vulnerable sections in the fuselage.  Statistical models can be developed to determine the reliability of the detection system according to the POD.

## *4.2 Experimental Results*

### *4.2.1 In-Situ Crack Imaging*

In developing this research, during the in-situ experimentation, a careful crack imaging process was carried out.  During each single step, the crack behavior was recorded.  As described in chapters II and III, a better knowledge about how a crack opens, closes, and grows is essential to develop strategies to reduce its harmful effects on aerospace structures. We used the microscopic images from the loading and unloading process and selected random points to measure local crack opening displacements (figure 48).

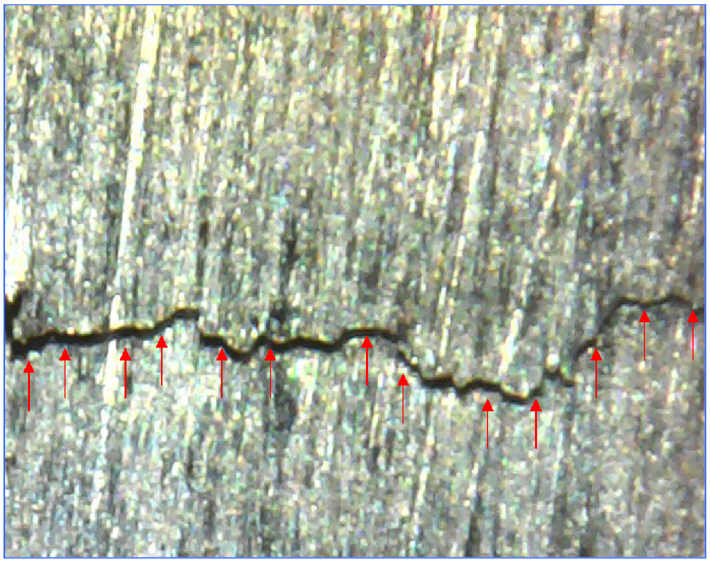


Figure 48: Complex Crack Morphology Analysis

As a detailed local crack measurement result, we obtained a plot represented by length of the crack from the root to the tip versus local crack opening displacement. Figure 49 shows an exponential decay trend in these local crack measurements for a random cracked specimen (LT-19) loaded at 351 lb. This is a valuable finding because it shows that even in small complex crack geometries, specific tendencies can be obtained at the microscopic level. This tendency agrees with the idealized linear crack (see figure 44). It would be enlightening to reproduce the real crack shape in the modeling software to check its consistency. However, for the purpose of this research, the scope is to determine whether those tendencies can be estimated, quantified and parameterized.

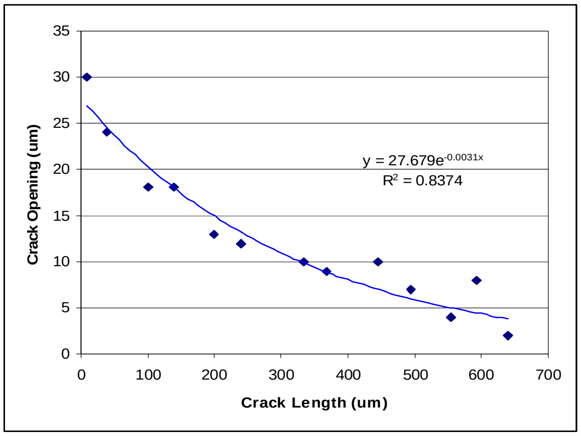



Figure 49: Experimental Local Crack Opening vs Crack Length

The next step, consentient with the computer-based models, was to assess the local experimental COD upon load application. The same specimen used to quantify the relationship between crack opening and crack length (LT 19) was used to research this attribute. A random point along the crack was selected and the local COD was measured at the various load levels.

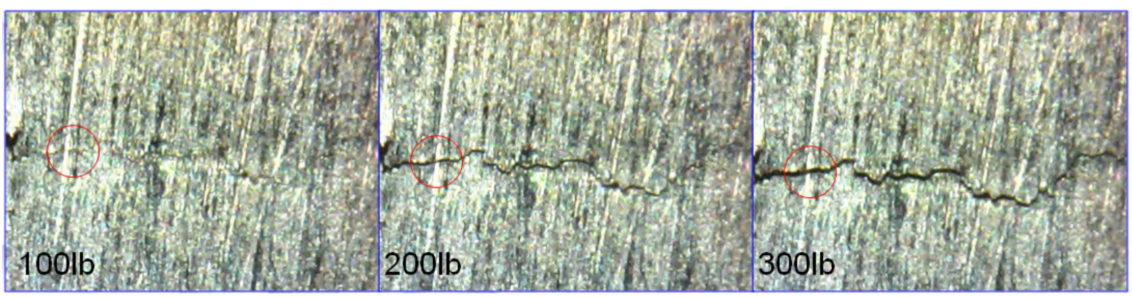



Figure 50: LT-19 Local COD Measurement

The respective measurements of the crack opening at the point indicated in figure 50 were recorded and plotted in figure 51 in which the maximum opening was 17um at 351 lbs and a linear trend in opening behavior was observed. There is an agreement between the model and the experiment.

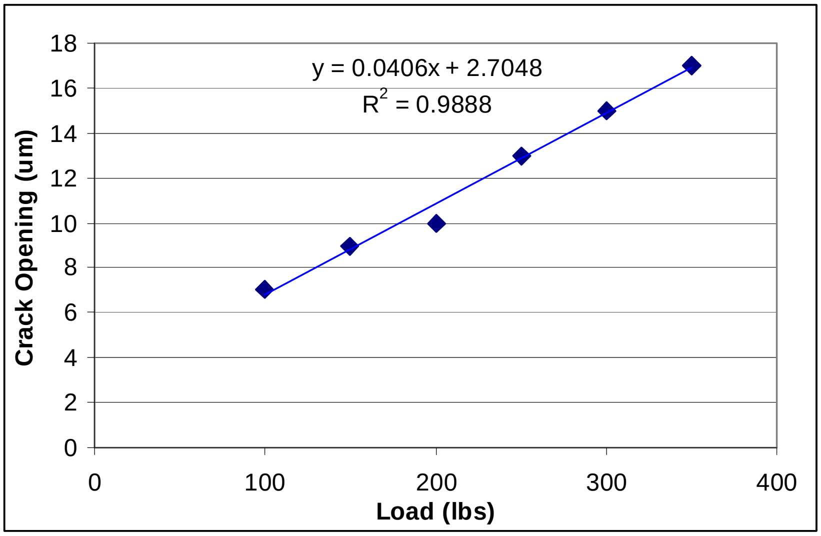



Figure 51: LT19 Local COD

### *4.2.2 In-Situ Bonded Piezo Sensing*

General benefits of using Lamb Waves in structural health monitoring include large propagation distance and through-thickness wave components. Rayleigh waves can propagate much longer distances with lower signal attenuation levels. These wave characteristics potentially allow for the monitoring of large areas with relatively few sensors, and the capability to detect both surface and internal structural defects.

The pitch-catch sensing was performed along the axis of specimen and loading direction. The pitch-catch method excites (pitches) a signal at one transducer then measures (catches) the signal at another transducer. Damage is detected by comparing the amplitude of the measured healthy responses to measured responses after damage is suspected to have occurred. If damage has occurred, the measured response will have decreased in amplitude. A set of lamb wave and surface wave signals for each stress level (see figures 52 and 53) were captured. In figure 52, higher peaks can be observed through the first part of the graph, followed by several weaker signals that show the many reflections from the Lamb waves Omni-directional behavior. The directional IDT Rayleigh wave in figure 53 shows a more consolidated burst pattern in time.

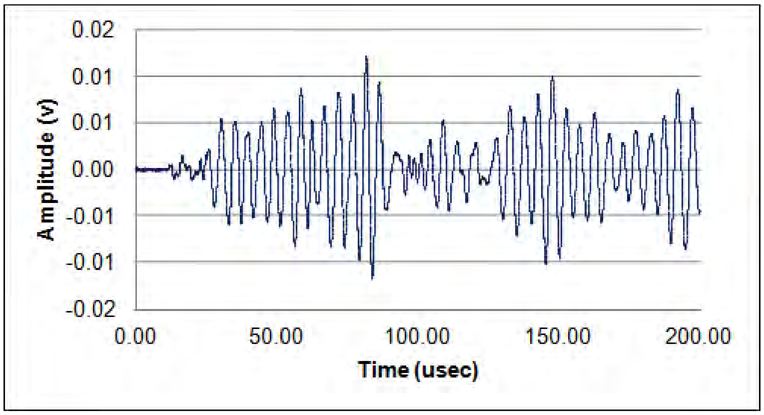



Figure 52: Lamb Wave Sensor - Multiple Reflections

The lack of reflected signals in figure 53 highlights the difference between the IDT signals with that of the multiple reflected signals collected using PZTs.

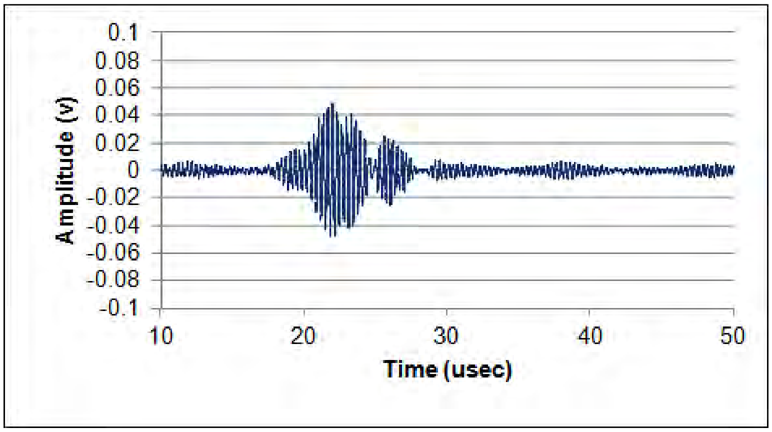



Figure 53: Surface Wave Sensor – Consolidated Tuneburst

A highly relevant assumption in this research was that a load would modify the ultrasonic signal in predictable rates. When analyzing the entire lifespan of a wave, the color scale might not depict the relevance of the peak-to-peak variation (Figure 54).

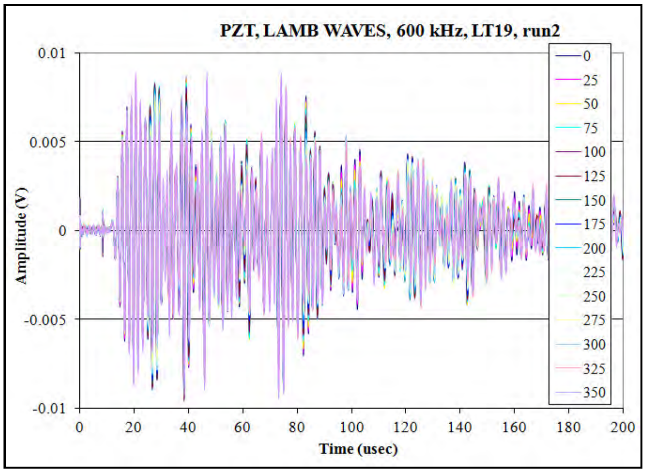



Figure 54: Superimposed Lamb Waves – 200 usec

However, in a closer view, being focused on specific plotted sections, it is possible to realize the effect of the wave amplitude and time differences due to load variations. The amplitude versus time for the LT19 specimen under 3.1 MHz in the IDT sensors and 600 kHz in the PZT´s is plotted in figures 55-57. This behavior was encountered in the three specimens at varied loads.

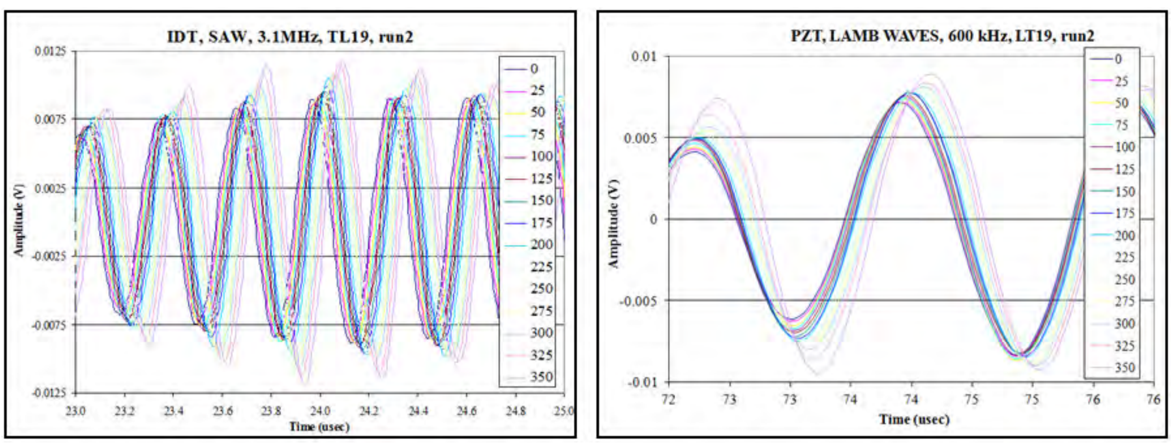



Figure 55: Amplitude Behavior in Superimposed Waves - 1

The peak-to-peak amplitude difference can be quantified and –as seen in figure 55- a consistent relation could be established between the applied load and the wave signal decrease.  An even closer view in figure 56 enables us to check the wave resulting in a weakening in the signal due to an increment in the effective crack length.

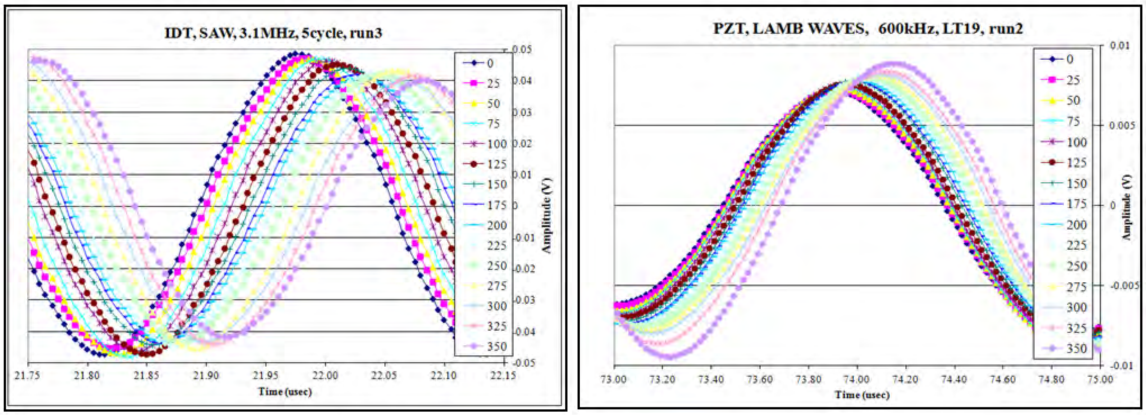



Figure 56:  Amplitude Behavior in Superimposed Waves – 2

For the PZT´s and the IDT´s, the amplitudes versus time were plotted and the signals after applied 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 300, 325 and 350 lb were offset on one graph for easy comparison in figure 57.  When viewed individually, the amplitude difference is not noticeable.  This is where the importance of comparing signals amplitudes resides.  The information given by the whole set of observations at varied loads will ultimately facilitate the detection of the crack.

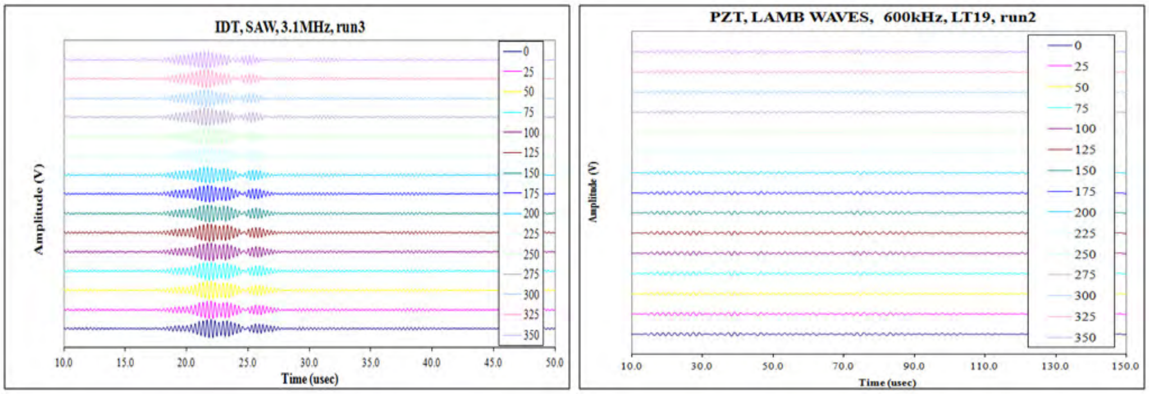



Figure 57: IDT and PZT Offset

The difference in the amplitude identified in figures 55 and 56, can be translated into a quantifiable value given by the peak-to-peak difference. The amplitude or peak-to-peak differences for specimens LT10, LT13 and LT19 after applied 600 kHz for the PZT´s and 3.1 MHz for the IDT´s is plotted in figure 58. These trends are consistent with the theoretical and model-based plots giving a strong linear relationship with a highly consistent $R^2$ (Figure 58).

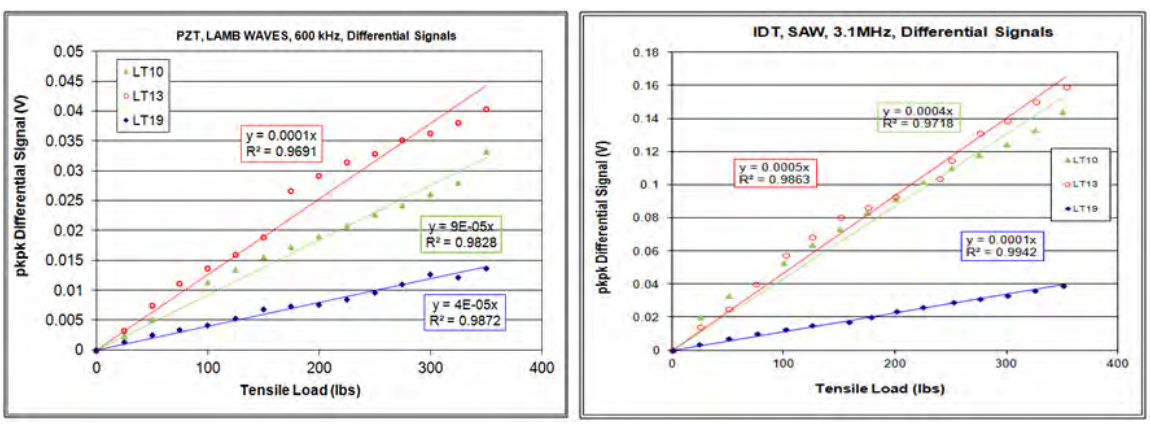



Figure 58: IDT and PZT Differential Signals

The composite graph in figure 59 shows that the peak-to-peak vs load relationship shown in figure 58, are virtually applicable to the various spectrums (100 kHz to 600 kHz for PZT´s and 3.1 MHz fot IDT´s) used for this research.  Trends are similar and predictions can be drawn based on their observed behavior.

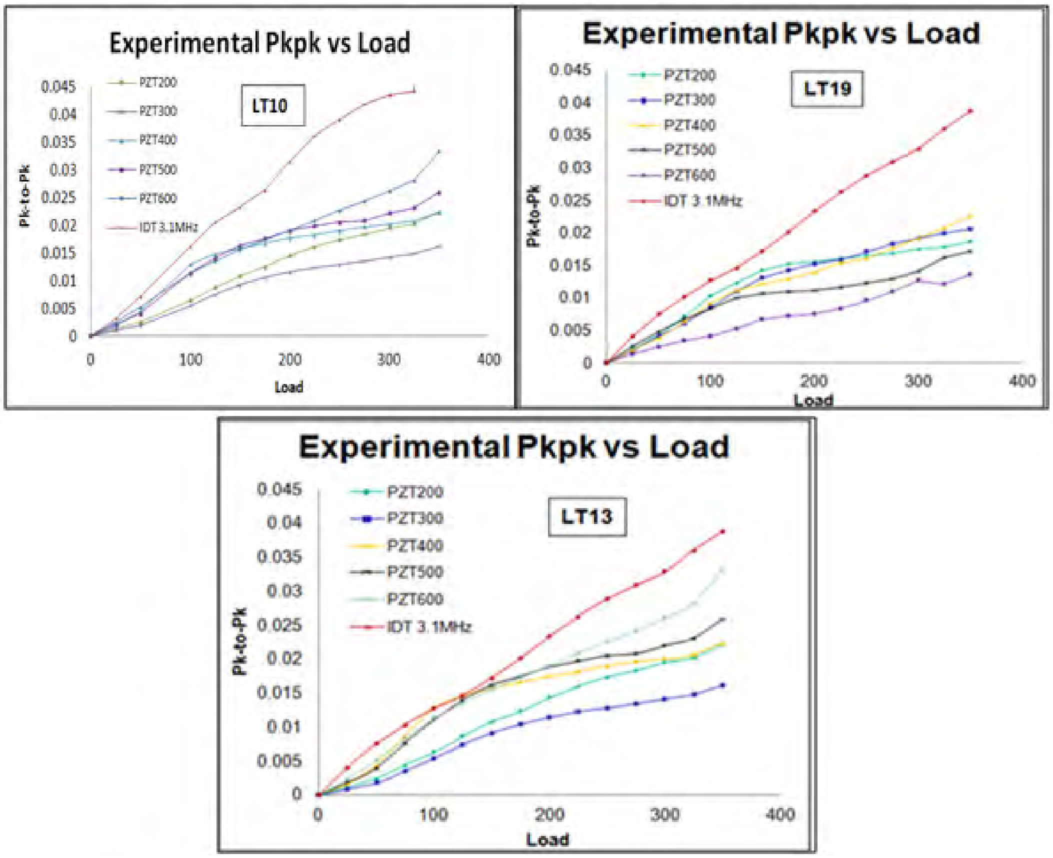



Figure 59:  Pk-to-pk vs Load for Specimens LT10, LT13 and LT19

### 4.3 *Systems Engineering Approach*

#### 4.3.1 *Fatigue Management Program*

Throughout this thesis, a description of meaningful policies, programs, fielded systems, efficient maintenance strategies and a renewed ultrasound inspection approach with improved capabilities has been provided.  For these components to achieve high levels of performance, an enhanced method to detect, size and track cracks must be implemented with the capabilities discussed through this report.

The Real-Time and on-Demand Fatigue Management Program represented in figure 60 is a feasible systems engineering approach that uses current technologies and develops/integrates some others to reach a higher level of efficiency. The Real-Time Aircraft Structural Health Monitoring is the suggested approach because by nature, it provides constant feedback to the MCC. However, this system could be implemented under the on-demand requirements which would provide more reliable results than current approaches due to the proven characteristics for detection, sizing and tracking here discussed. The proposed real-time and on-demand FMP block diagram is depicted in figure 60. This is a generic diagram where previously discussed concepts and programs (Chapter II) such as NAARP, DTA, SIP, ASIP, RAPID, FCL, CBM, HVM, etc can be introduced at their specific level of application. The diagram is presented generically because different programs, different country regulations, and different policies relate to the same structure.

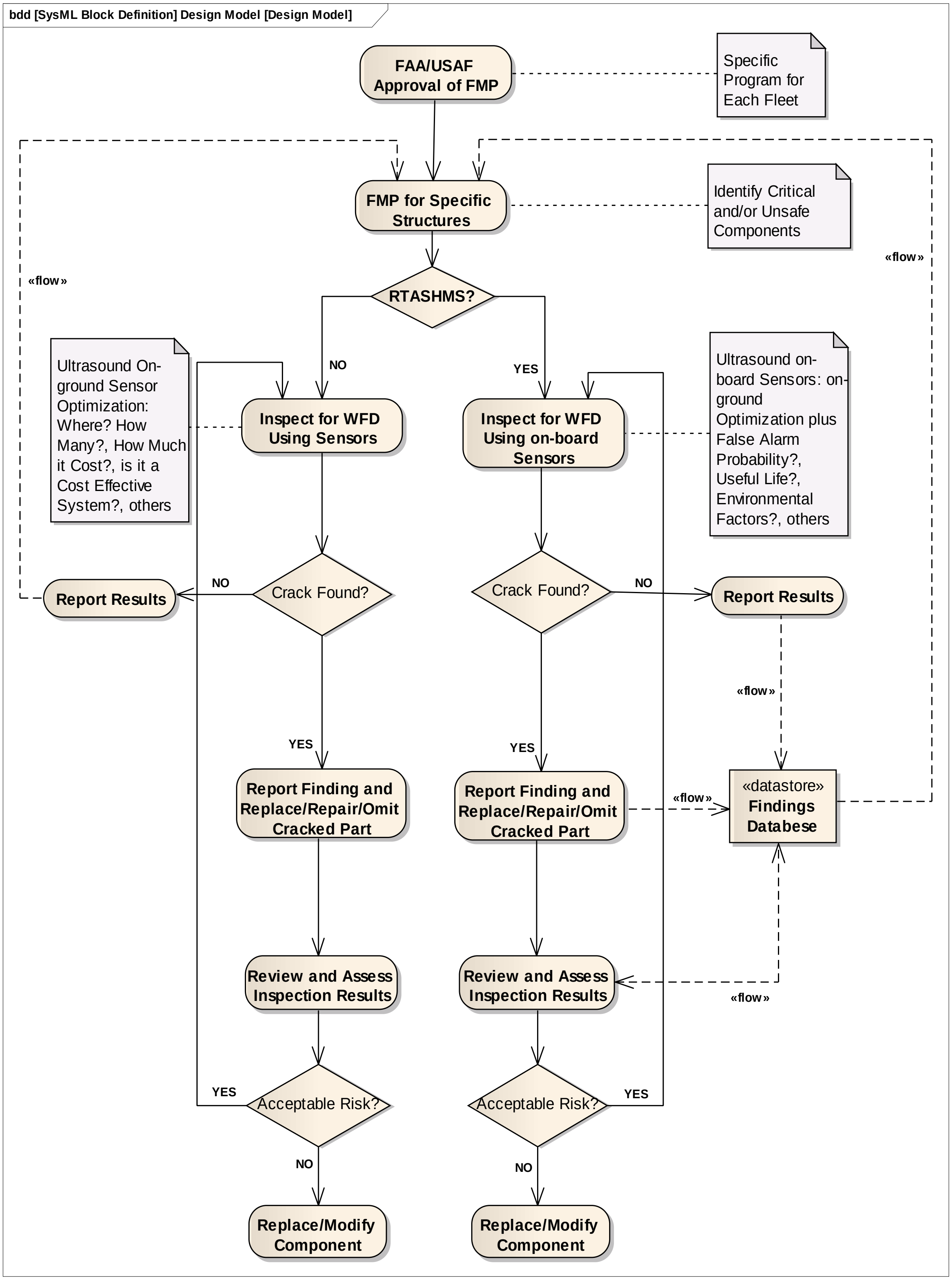



Figure 60: Real-Time and on-Demand Fatigue Management Program

Figure 61 depicts the Ultrasound-Based SHM procedures proposed by this research. It is important to highlight the need of developing a framework to assess a meaningful peak-to-peak signal variation. With this research, it has been demonstrated with theoretical concepts, simulations and in-situ experimentation that the system is feasible. By using a combination of calculations, simulations and experiments/measurements, clearly define crack characteristics can be estimated and specific baselines to provide the assessment prediction parameter can be established.

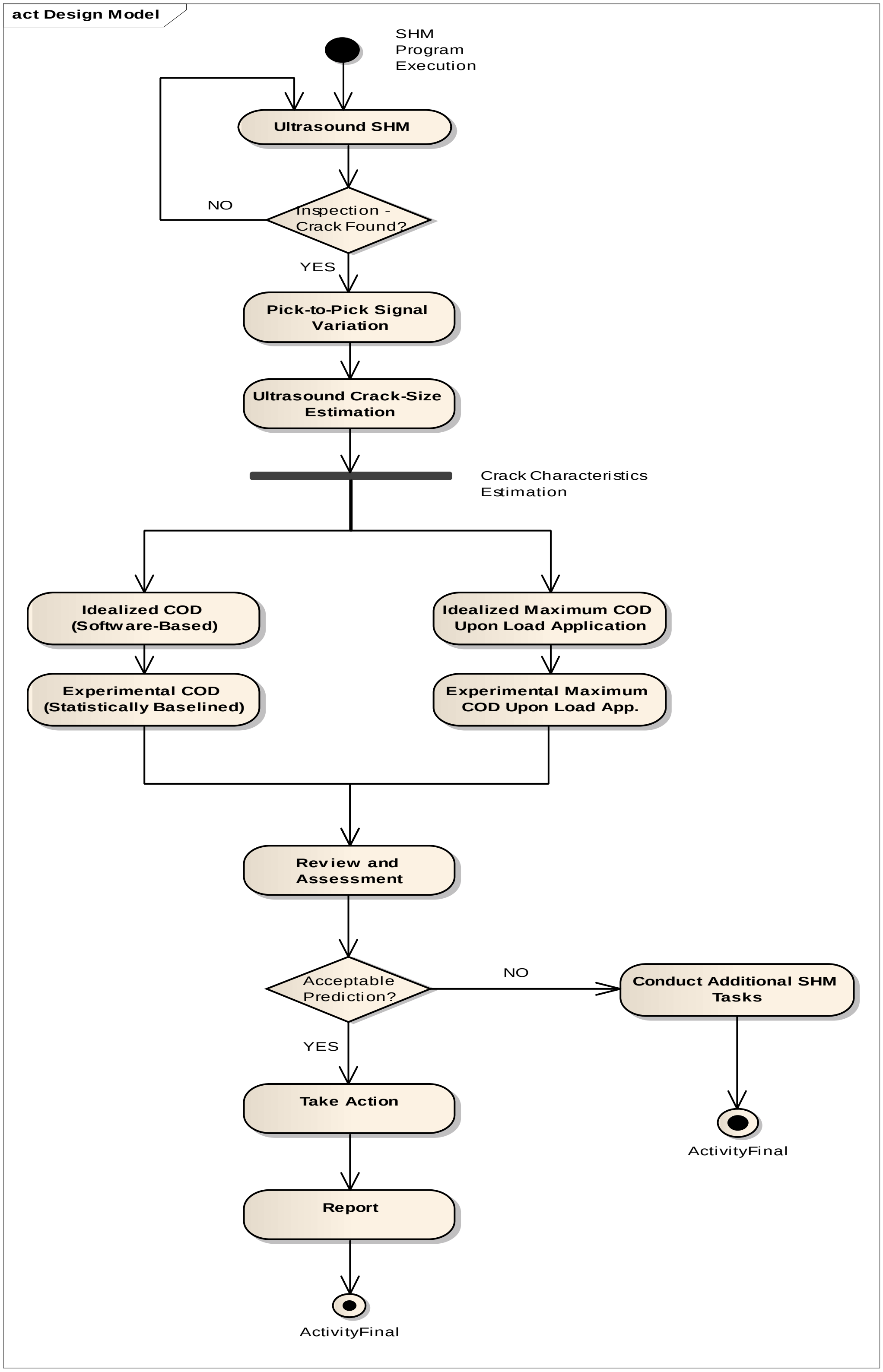



Figure 61: Ultrasound-Based SHM Inspection

## *V. Conclusions*

This thesis studied the use of PZT and IDT sensors to generate Lamb and Rayleigh waves in aluminum dogbone specimens under axial load for improved fatigue crack detection and quantification. The goal was to assess how the ultrasound wave vs load interaction could provide a consistent method to detect, size, and track small length, multiple site fatigue damage in a pressurized fuselage. The study used Verification methods since analysis, tests or demonstration, simulation, operational data and examination were carried out throughout a series of theoretical considerations, prototype modeling and in-situ experiments. Finally, an enhanced Fatigue Management Program (FMP) was presented based on the proposed ultrasound Structural Health Monitoring inspection.

### *5.1 Crack Detection, Sizing and Tracking Discussion*

This thesis explored an innovative way to implement a structural health monitoring method. With small loads applied to a simulated fuselage skin under observation, it was possible to increase the probability of cracks detection. The approach has the potential capability of reducing the sensors required to do an inspection, to improve probability of early failure detection due to cracks and reduce the time required to perform monitoring tasks.

Accidents occurring in the past may be mitigated using the improvements described in this thesis. However, it must be admitted that fatigue predictions on the crack initiation and early growth life are still problematic and the impact of MSD on the structural residual strength is still unknown. They cannot be satisfactory solved without relevant fatigue tests. Current crack detection capabilities are uncertain because they are dependent on issues such as people skills, techniques being used, effective vs real crack length and so forth. This research demonstrated that fatigue crack detection, sizing and tracking in structures are possible with a higher POD.

The three possible approaches to solve the problem were explored (theoretical, computer-based and experimental) achieving excellent consistent results. It is possible to establish theoretical, model-based and baselines to quantify the COD and the ultrasound signal decay when the wave interacts with the crack. It is possible to determine the load required to obtain a specific COD. In most of the previous research, crack behavior parameters were qualified according to specific conditions. This thesis gives a frame to actually quantify relevant crack characteristics for SHM purposes.

Although the PZT´s -due to their mode of operation- reflect multiple signals, the peak-to-peak analysis provided similar outcomes than the IDT´s. The amplitude difference cleans up the “noise” generated by the multiple reflections providing a unique evaluation parameter.

### *5.2 Systems Engineering Discussion*

The SHM system proposed in this research is intended to be testable, scalable, repeatable, reliable, sustainable, upgradable, environmental compatible and deployable across the aviation community and requires a detailed understanding of tools for analysis, simulation, assessment, synthesis, costing, etc. Moreover, because multi-disciplinary aspects characterize the full problem setting, it is highly important to present relevant courses of action among the whole aviation community. Each stakeholder must contribute in the system tuning up.

The primary goal in the systems engineering approach was to research the available capabilities and identify how a combination of existing methods can be complemented by a scientific development to potentiate the overall ISHM system. The proposed FMP is consequent with AFSO21and Lean Operations by eliminating waste in the process, with Six Sigma by reducing the process variability and inducing procedures standardization while incrementing the samples sizes for analysis and its potential benefits are outstanding to increase the aviation safety and fit in maintenance strategies such as condition-based maintenance and high velocity maintenance.

### *5.3 Future Research*

A wide research spectrum is available to complement this research. In this section, there are listed some proposed by the author.

- Real crack shape software modeling: This thesis was developed in the basis of a real experimental crack vs an idealized linear model. It would be illuminating if the exact shape can be reproduced to assess what is the impact in the outcome.
- Repeat procedures to verify and validate results: An experimental research with verification and validation methods will provide a consistent baseline.
- Crack Monitoring using replication methods (i.e., cellulose acetate replication method): This research will explore deeply the crack characteristics.

- Applying bending loads: In the aircraft skin, there are mainly applied axial and bending loads. This thesis explored only the axial load. Valuable information can be collected if bending or collaborative (axial and bending loads) are applied.
- Pipe-shaped structure study (Geometric nonlinear effect): Tests with the real shape will provide information about how the shape affects the peak-to-peak signal.
- Reliability Analysis: Experimental tests placing the sensors in random locations and distances to determine appropriate configurations keeping an acceptable probability of detection.
- Optimization and Cost Analysis: With the enhanced detection approach, how many sensors are required to reliably monitor a section?. What is the economic impact of this configuration?
- Specific requirements to integrate and improve the FMP system. The system components are deployed but their integration requires systems engineering involvement.

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**14. ABSTRACT**
This effort constitutes a systems engineering approach in which the materials science, ultrasound structural health monitoring, flight and maintenance operations, and relevant aeronautical policies and programs are involved to explore the evolution and characterization of structural cracks in aircraft fuselage structures in which the loads are varying. During flight, an aircraft fuselage skin and structure are subjected to varied cyclic loads, which can cause embedded cracks and other damage features to change their characteristics due to loading effects. The current research is based in the application of finite element modeling techniques using COMSOL and PZFLEX software to characterize the behavior of a crack under static loads as well as experimental techniques to observe the behavior of cracks under different static loads, with the goal of understanding the interaction of ultrasonic energy with opening-closing crack features. Specimen testing under tensile loads were considered, where crack detection and crack characterization were studied for bonded piezoelectric sensing and guided ultrasonic waves useful in structural health monitoring applications. The results suggest that crack detection and crack sizing accuracy can be impacted by load-induced, crack opening-closure effects, where linear elastic loading of the structure resulted in linear changes in the ultrasonic signal response.

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